## QUALITY EVALUATION LABORATORY

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# QUALITY EVALUATION LABORATORY UNITED STATES NAVAL AMMUNITION DEPOT CRANE, INDIANA

EVALUATION PROGRAM
FOR
NICKEL CAUMIUM SEALED CELLS

FIRST QUARTERLY REPORT
OF
LIFE CYCLING TEST

QE/C 64-274

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Enclosure (1)

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## REPORT BRIEF

## SEALED NICKEL CADMIUM BATTERY PROGRAM

OF

## CELLS DESIGNED FOR USE IN SPACECRAFT

- Ref: (a) National Aeronautics and Space Administration Purchase
  Order Number W11.252B
  - (b) NASA ltr BRA/VBK/pad of 25 September 1961 w/BUWEPS first end FQ-1:WSK of 2 October 1961 to CO NAD Crane
  - (c) Preliminary Work Statement for Battery Evaluation Program of 25 August 1961

## I. TEST ASSIGNMENT BRIEF.

- A. In compliance with references (a) and (b), evaluation of sealed nickel cadmium cells was begun according to the program outline of reference (c). This is the first quarterly report of the cycle life test, the third phase of the evaluation program of sealed nickel cadmium cells. It covers the work for the period ending 31 March 1964. The acceptance tests and general performance tests, the first and second phases of the evaluation program of sealed nickel cadmium cells, were reported earlier.
- B. The object of this evaluation program is to gather specific information concerning sealed nickel cadmium cells designed for use in spacecraft. Information concerning the performance characteristics and limitations, including cycle life under various electrical and environmental conditions, will be of interest to power systems designers and users. Cell weaknesses, including causes of failure of present designs, will be of interest to suppliers as a guide to product improvement.
  - C. The life cycling test was begun in December 1963.

## II. PRELIMINARY TESTS.

- A. Acceptance Tests. The acceptance tests were started on 24 September 1962, with the completion date extended to 16 August 1963 because of delays in getting the full quantities of cells required and the necessary replacements.
- 1. Cells were purchased by the National Aeronautics and Space Administration (NASA) from four manufacturers.
  - 2. All samples were subjected to the following acceptance tests:
    - a. Capacity discharge test.

- b. Overcharge test.
- c. Internal resistance.
- d. Cell short test.
- e. Mechanical leakage test.
- 3. Samples failing to pass the above tests were returned to the supplier for replacement. The replacements were subjected to the same tests and the process continued until the required number of each type, listed below, had been accepted from each respective supplier.

Rated Capacity	Supplier	Number of Cells Required
3.0 ah	General Electric Company	200
3.5 ah	Gould-National Batteries, Inc.	200
5.0 ah	Sonotone Corporation	200
6.0 ah	Gulton Industries, Inc.	200
12 ah	General Electric Company	100
20 <b>a</b> h	Gould-National Batteries, Inc.	100
20 ah	Gulton Industries, Inc.	100

- B. General Performance Tests. The general performance tests began on 6 May 1963 and were completed on 15 November 1963.
- 1. Five cells of each type were chosen for the general performance tests.
- 2. The tests were performed at existing humidity and atmospheric pressure and at three specific temperatures. The tests and test temperatures were as follows:
  - a. Vibration test at room ambient temperature.
  - b. Mechanical shock test at room ambient temperature.
  - c. Acceleration test at room ambient temperature.
- d. Charge and discharge voltages versus time at 0°C, 25°C and 50°C.
  - e. Overcharge characteristics at 0° C, 25° C and 50° C.

f. Charging efficiency at 0° C, 25° C and 50° C.

## III. SUMMARY OF CYCLE LIFE TEST RESULTS.

## A. Number of Cycles Completed.

- 1. Forty-two of the 84 packs are cycling in a 90-minute orbit period and have completed from 551 to 1819 cycles as of 31 March 1964. The remaining 42 packs, cycling in a 3-hour orbit period, have completed from 358 to 800 cycles.
- 2. The number of cycles completed by each pack is given in Table V, page 54.
- B. Cycling Performance. It was found that the majority of packs cycling at 50° C ambient temperature would not cycle satisfactorily with the specified currents and orbit periods. All but four of these packs were changed to a 40° C ambient temperature.

## C. Cell Failures.

1. There were 32 cell failures during the first quarter. These are summarized below according to test condition:

Test Temperature at Time of Failure (°C)	Percent Depth of Discharge	Orbit Period (Hours)	Number of Failures to Date
50 50 50 50	25 25 15 15	1.5 3 1.5	3 2 2 0
40 40 40 40	25 25 15 15	1.5 3 1.5 3	5 3 0 0
25 25 25 25 25	40 40 25 25	1.5 3 1.5 3	6 6* 2 0
• 0 0 0	25 25 15 15	1.5 3 1.5 3	0 0 2 1

<sup>\*</sup> Four of these six were from the same 5-cell pack, which constituted failure of the pack.

- 2. Cell failures and results of failure analysis are listed in greater detail in Table VI, page 55. Cell failures are summarized according to cell type and test conditions in Table VII, page 56.
- D. It is felt that further analysis of cycle life results would be premature at this time.

## CYCLE LIFE TEST

OF

## SEALED NICKEL CADMIUM CELLS

## I. INTRODUCTION.

- A. Considerable research is being done to find more efficient and reliable means of storing electrical energy for orbiting satellites and similar applications. Rechargeable cells offer one such means. The test program at NAD Crane has been established in order to further the evaluation of certain types of cells and to obtain performance and failure data as an aid to their continued improvement.
- B. This, the first quarterly report on the cycle life test, which is the third phase of the evaluation program of sealed nickel cadmium cells, covers the work for the period ending 31 March 1964. The first phase of this program, the acceptance tests, is described in paragraph IV.A., and was reported earlier. The second phase of this program, the general performance tests, also reported earlier, is described in paragraph IV.B.
- C. On 5 December 1963 this activity began the cycle life test on 660 of the 1100 cells purchased by National Aeronautics and Space Administration (NASA). The cells were from four manufacturers, and consist of seven sample classifications ranging from 3 to 20 amperehours.
- D. The purpose of the cycle life program was to determine the cycling performance capabilities of packs of the cells under different load and temperature conditions. The load conditions include cycle lengths (orbit periods) of 90 minutes and 3 hours and depths of discharge ranging from 15 to 40 percent. The cells are cycled under normal atmospheric conditions at temperatures of 0°C, 25°C, 40°C and 50°C. The packs are cycled until more than half of the cells of each pack have failed.
- E. Any cell packs and tests added later will be covered in this series of quarterly reports.

## II. CELL DESCRIPTION.

- A. General. Photograph 1 is a group picture of the seven cell types.
- 1. 3.0 Ampere-hour General Electric Company (G.E.): The cell container and the cell cover are made of stainless steel. The positive terminal is insulated from the cell cover by a ceramic

(titanium hydride) bushing and protrudes through the bushing with a solder tab welded to the terminal. The negative terminal is a solder tab welded to the cover.

- 2. 3.5 Ampere-hour Gould-National Batteries, Inc. (Gould): The cell container and the cell cover are made of stainless steel and serve as the positive terminal. The negative terminal is a pigtail type extension of the negative plate tab through the center of the cover. The negative terminal is insulated from the "positive" cover by a glass to metal seal.
- 3. 5.0 Ampere-hour Sonotone Corporation (Sonotone): The cell container and the cell cover are made of stainless steel. Two stainless steel tabs, welded to the cover, serve as contacts for the negative terminal. The positive terminal is a solder type extension of the positive plate tab through the center of the cover. The positive terminal is insulated from the "negative" cover by a ceramic seal. Two ring indentations, about 1/32 inch deep, located approximately 7/8 inch from either end of the cell can, were crimped after cell assembly to hold the element snugly in the cylindrical can.
- 4. 6.0 Ampere-hour Gulton Industries, Inc. (Gulton): The cell container and the cell cover are made of stainless steel. The positive terminal is insulated from the cell cover by a ceramic seal, while the negative terminal is welded to the cover. Both terminals protrude through the cover as solder type terminals.
- 5. 12.0 Ampere-hour General Electric Company: The cell container and the cell cover are made of stainless steel. Both terminals are insulated from the cell cover by ceramic seals and protrude as 1/4-20 threaded posts.
- $6.\ 20.0\ \text{Ampere-hour}$  Gould-National Batteries, Inc.: The cell container and the cell cover are made of stainless steel. Each of the terminals is insulated from the can by a nylon seal and protrudes as a 1/4-28 threaded post. The cells, equipped with pressure relief valves instead of being sealed as specified, were returned to the manufacturer to be sealed after completion of the acceptance tests. The manufacturer sealed the cells by encasing each individual cell in a mold of epoxy resin.
- 7. 20.0 Ampere-hour Gulton Industries, Inc.: The cell container and the cell cover are made of stainless steel. Both terminals are insulated from the cell cover by a ceramic seal and protrude through the cover as solder type terminals.

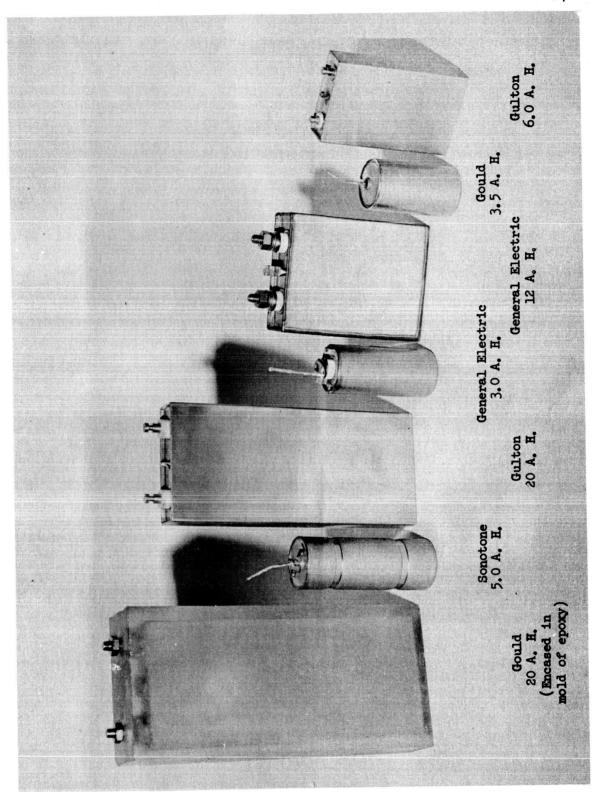
## B. Dimensions and Weight.

1. The dimensions, weight and case polarity for each of the seven types of cells are tabulated in Table I.

TABLE I

PHYSICAL CHARACTERISTICS OF CELLS

	Remarks						Before Epoxy Cover	After Epoxy Cover	
	Case Folarity	Wegative	Positive	Negative	Negative	}	!	ł	!
	Average Weight (Grams)	155.0	135.2	237.4	267.0	562.0	1045.0	1423.0	871.6
Average Dimensions (Inches)	Length or Depth	1	;	ł	0.81	1.11	16.0	1.49	06.0
	Width or Diameter	1.25 D	1.28 D	1.31 D	2.09 W	3.02 W	3.05 W	3.56 W	2.98 W
	Height Base to Top of Terminal	3.10	2.22	3•67	3.68	4.59	7.95	8.10	7.10
	Shape	Cylindrical	Cylindrical	Cylindrical	Rectangular	Rectangular	Rectangular		Rectangular
	Manufacturer's Rated Capacity (Ampere-hours)	3.0	3.5	5.0	0.9	12.0	20.0		20.0
	Manufacturer	G.E.	Gould	Sonotone	Gulton	G.E.	Gould		Gulton



Group Picture of Cell Types PHOTOGRAPH 1

## III. DESCRIPTION OF CYCLE TEST.

- A. Cycle Life Tests. These tests are a study of the effects of the cycle period, environmental temperature, percent of recharge, and depth of discharge on the cycle life of the test samples.
- 1. The program includes a total of 12 combinations of test parameters. Cells, of comparable capacities, of each of the seven types were grouped into packs, with one pack of each type per combination of parameters. Each of the 84 packs thus obtained continues cycling at its particular combination of parameters until it has failed.
- 2. The 3.0 ampere-hour (ah), 3.5 ah, 5.0 ah and 6.0 ah packs consist of 10 cells each. The 12 ah and 20 ah packs consist of five cells each.
  - 3. The test parameters are as follows:
- a. Three environmental temperatures, with corresponding percentages of recharge.
  - (1) 0 ± 2° C, with 115 percent recharge.
  - (2) 25 ± 2° C, with 125 percent recharge.
  - (3) 50 ± 2° C, with 160 percent recharge.
- b. At each of the three temperatures, two depths of discharge.
  - (1) At 0° C, 15 and 25 percent depths of discharge.
  - (2) At 25° C, 25 and 40 percent depths of discharge.
  - (3) At 50° C, 15 and 25 percent depths of discharge.
  - c. Two orbit periods for all three temperatures.
- (1) 90 minutes (30 minutes of discharge, 60 minutes of charge).
- (2) 3 hours (30 minutes of discharge, 150 minutes of charge).
- 4. Voltage limits on charge were specified according to temperature. These are average voltages, per cell, for the entire pack.
  - a. At 0° C, 1.55 volts per cell, average.

- b. At 25° C, 1.49 volts per cell, average.
- c. At 50° C, 1.41 volts per cell, average.
- 5. After a short period of cycling it became apparent that the majority of the 28 packs cycling at 50° C would not continue to cycle satisfactorily at that temperature.
- a. The ambient temperature for all but four of these 28 packs was therefore reduced from 50°C to 40°C, and shortly thereafter the charge voltage limit raised from 1.41 volts per cell to 1.45 volts per cell.
- b. The remaining four packs were left cycling at the original 50° C, since it appeared that they would continue to function satisfactorily at that temperature, with the reservation that they be likewise changed to a 40° C ambient temperature whenever they failed to do so. The four packs are cycling at 25 percent depth of discharge. The cell types and orbit periods are as follows:
  - (1) G.E. 3.0 ampere-hour, 90-minute orbit.
  - (2) Gould 3.5 ampere-hour, 3-hour orbit.
  - (3) Gould 20 ampere-hour, 3-hour orbit.
  - (4) Gould 20 ampere-hour, 90-minute orbit.
- c. Before the change from 50° C to 40° C, on the 24 packs, the percent of recharge on the Gulton 6.0 ah pack cycling at 25 percent depth of discharge, 3-hour orbit, was temporarily raised from 160 to 200 percent in an attempt to improve cycling performance. Cell voltages continued to drop, however, and this pack was changed to a 40° C ambient with 160 percent recharge.
  - 6. Table II is a summary chart of all test conditions.

## B. Discharge and Charge Currents.

- 1. All discharges are conducted at specified constant current rates. All charging is done at specified constant current rates until the maximum specified on charge voltage limit for the respective temperature condition is reached, at which time charging continues at the specified maximum voltage limit with corresponding reduction of the current rate.
- 2. All currents were based on the manufacturer's rated amperehour capacity. The letter c, as used in this report, is a symbol for that current value, in amperes, which is numerically equal to this

capacity. For example, in the case of a cell rated at 3.0 amperehours capacity, a discharge or charge current of c/10 would be 300 milliamperes.

a. The depth of discharge, which is the percent of a cell's rated capacity drawn from the cell, is expressed by the following formula: Discharge Current (Amperes) x Hours = Percent Depth of Discharge x Rated Capacity.

$$I_d \times Hours = \frac{D}{100} \times c$$

Since the discharges of the 90 minute and 3 hour orbit periods are one-half hour long, the discharge current for either orbit period may be found by the simplified formula:

$$I_d = 0.02 De$$

amperes ( $I_d = 0.02 \times 15 \times 3 = 0.90 \text{ amperes}$ ).

where: I<sub>d</sub> = discharge current in amperes
D = percent depth of discharge required
c = rated capacity of the cells.

For example, a pack composed of 3.0 ampere-hour cells, to be discharged to a depth of 15 percent, would require a discharge current Id of 0.9

b. The percent of recharge is most easily defined operationally as follows: If  $Q_d$  is the number of ampere-hours to be removed from the pack on discharge and  $Q_c$  the number of ampere-hours to be returned on charge, then  $Q_c = Q_d$  x Percent of Recharge. Expressed in terms of currents, this becomes  $I_c \times T_c = I_d \times T_d \times Percent$  Recharge,

where:  $I_c$  = charge current in amperes  $T_c$  = length of charge, in hours  $I_d$  = discharge current in amperes  $T_d$  = length of discharge, in hours.

For example: In the case of a 3.0 ampere-hour pack, 90 minute orbit (30 minutes discharge, 60 minutes charge) 15 percent depth of discharge and 115 percent recharge, the charging current would be;

$$I_{c} = \frac{I_{d} \times T_{d} \times Percent Recharge}{T_{c}}$$

$$= \frac{(0.02 \times 15 \times 3) \times 0.5 \times 1.15}{1}$$

= 0.518 amperes.

In the case of a 3.0 ampere-hour pack, 3 hour orbit (30 minute discharge, 150 minutes charge), 25 percent depth of discharge and 125 percent recharge, the charging current would be:

$$I_c = \frac{(0.02 \times 25 \times 3) \times 0.5 \times 1.25}{2.5} = 0.375 \text{ amperes.}$$

## C. Failure Criteria.

- 1. A cell is considered to have failed when the terminal voltage drops below 0.5 volts at any time during a regular discharge-charge cycle. It is removed from the pack upon completion of the cycle. A pack is considered to have failed when more than one-half of its cells have failed.
- 2. Cell failures and results of failure analysis are listed in greater detail in Table VI, page 55. Cell failures are summarized according to cell type and test conditions in Table VII, page 56.

## TABLE II

## SUMMARY OF TEST PARAMETERS

For each orbit period, one pack of each of the seven cell types is cycling at each of the six temperature-depth of discharge combinations.

ORBIT PE 90 Min and 3 Hours	utes				
Discharge Time	Charge Time	Temperature °C	Percent Recharge	Percent Depth of Discharge	On-Charge Voltage Limit Ave./Active Cell
		(50*)	(160**)	(15) (25)	(1.41)
Minutes	Minutes and	40 .	160	15 25	1.41 (Changed to 1.45)
30 Mir	60 Min and 2.5 Hoo	25·	125	25 40	1.49
		0	115	15 25	1.55

<sup>\*</sup> All but four packs changed to 40° C ambient.

<sup>\*\*</sup> One pack of Gulton 6.0 ah cells at 50° C was temporarily raised to 200 percent recharge, but this was not sufficient to maintain normal cycling.

## IV. PRELIMINARY TESTS.

## A. Acceptance Tests.

- 1. Each cell, upon receipt, was weighed and measured, and tested for leaks and electrical shorts. In addition, the capacity, the internal resistance, and the overcharge steady state voltages of each cell were determined.
- 2. Cells which showed leakage under atmospheric or reduced pressure, or which showed an internal short were returned to the manufacturer for replacement.

## B. General Performance Tests.

## 1. Summary of tests performed.

- a. Five cells of each of the seven cell types were used for the general performance tests. Of these five, two were of above average ampere-hour capacity (as determined by the acceptance tests), one was average, and two were below average.
- b. All tests were performed at existing room atmospheric pressure.
  - c. A list of the tests is as follows:
    - (1) Vibration at room ambient temperature.
    - (2) Mechanical shock at room ambient temperature.
    - (3) Acceleration at room ambient temperature.
- (4) Charge and discharge voltages versus time at 0°C, 25°C and 50°C.
  - (5) Overcharge characteristics at 0° C, 25° C and 50° C.
  - (6) Charging efficiency at 0° C, 25° C and 50° C.
- 2. Description of Tests. Only tests (4), (5) and (6) of paragraph IV.B.1. will be reviewed with additional comments and comparisons. They were performed in the order in which they are discussed. The same five cells of each type were used throughout these tests, with replacements being made only in the event of cell failure during the tests. Since many of the charge rates are considerably in excess of the manufacturers' recommendations, the possibility that some test results may have been affected by preceeding tests should be noted. Paragraphs a, b and c below are descriptions of the three tests. Paragraph d is a discussion of the results.

## a. Charge and Discharge Voltage Versus Time.

(1) Each cell was charged and discharged at ambient temperatures of 0° C, 25° C and 50° C, at each of the rate combinations shown below. Each charge-discharge combination at each of the three temperatures was repeated until essentially identical cycles were obtained.

Charged At	Discharged At
c/10 amperes for 16 hours	c/5 amperes
c/10 amperes for 16 hours	c/2 amperes
c/5 amperes for 8 hours	c/5 amperes
c/5 amperes for 8 hours	c/2 amperes

- (2) For each cell the voltage on charge was limited to 1.50 volts, and the discharge cutoff voltage was 0.9 volts.
- (3) For each of the seven cell types, Table III gives the averaged capacities of the five cells tested, for each of the charge-discharge-temperature combinations. It also includes the average of their acceptance test capacities.
- (a) The acceptance test capacities were measured at 25° C, at the c/2 rate to a cutoff of 1.00 volt per cell.
- (b) Figure 1 is a comparison of the average capacities of the seven types under the various charge-discharge-temperature conditions with their average acceptance test capacities. The points were obtained by dividing the ampere-hours given in Table III by the corresponding average acceptance test capacities. The acceptance test capacities, therefore, represent the 100 percent line across the chart. The capacities of any of the seven cell types under any of these conditions may be compared with one another visually, or by a ratio of the percentages shown in the figure. For example, the average capacity of the General Electric Company 3.0 ampere-hour cells under the c/10, c/5, 50°C charge-discharge-temperature combination is 61 percent of their average acceptance test capacity. Their capacity under the c/5, c/5, 25°C combination is 104 percent of their average acceptance test capacity. Therefore, the first capacity is 61/104 = 58.6 percent of the second.

## b. Overcharge Characteristics.

(1) At each of the three temperatures, the fully charged cells were to be placed on continuous charge at the c/10, c/8, c/6, c/4, c/2 and c/1 rates, in that order. Each rate was maintained until it was clear that the cell voltages had stabilized, at which time the charge current was increased to the next higher rate. The series of six rates was performed at 0° C, 25° C and 50° C ambient temperatures, in that order.

- (2) The charge voltage limit was 1.55 volts. When any cell voltage exceeded this limit the cell was removed from test until the remaining cells were to be tested at the next higher temperature.
- (3) Cells which showed a temperature above 77° C at the positive terminal were also removed from test. Where this occurred at 25° C ambient, any such cells were returned to the group under test when the ambient temperature was raised to 50° C.
- (4) Figure 2 shows the average steady-state voltages of each of the seven cell types, at each charge rate, at both 25° C and 50° C. No points are shown for the 0° C ambient temperature, since all cells reached the 1.55 volt limit at the c/10 rate and the test at that temperature was discontinued.
- (a) Steady state voltages are connected by solid line segments (25° C) or dotted line segments (50° C). Where a line segment is interrupted by a numbered symbol, it indicates the number of cells which were removed from test prior to reaching the next stabilizing point, for the reason indicated by the shape of the symbol.
- (b) The two points connected by each line segment are averages for only the cells which stabilized successfully at both rates. For example, at 25° C, all five of the G.E. 12 ah cells stabilized at the c/10, c/8, c/6, c/4 and c/2 rates. At the c/2 rate, their average stabilizing voltage was 1.372 volts, as shown. At the c/1 rate, however, three cells were discontinued due to thermal runaway, and only two cells were able to stabilize. The average stabilizing voltage of these two cells, at the c/2 rate, was 1.385 volts, which is the other end of the line segment extending to the c/1 rate. Symbols to the immediate left of the c/10 point indicate cells which reached the voltage limit without stabilizing at the c/10 rate.

## c. Charging Efficiency.

- (1) This test was a measure of the ampere-hours which could be obtained on discharge after varying periods of charge at each of five charging rates, and at 0°, 25° and 50° C. At each rate, the test consisted of a series of charge and discharge cycles for which the charge period was progressively lengthened until it became apparent that any further increase in the length of charge would yield no further increase in the ampere-hours delivered on discharge. Each series was preceded by a normalizing cycle consisting of an 8-hour charge at c/5 followed by a discharge at c/2 to a cutoff of 1.0 volt.
- (2) The charge rates used were c/10, c/24, c/16, c/5 and c/l in that order, with the charge voltage limited to 1.50 volts. All discharges were at the c/2 rate to a cutoff of 1.0 volt.

- (3) The duration of the first charge period in each series was such that the number of ampere-hours delivered to the cell was equal to one-half of the cell's rated capacity, with succeeding charge periods increased by uniform increments.
- (4) The five cells of each type were divided into three groups for testing, as follows:
- (a) Two cells (one above average capacity and one below) to be tested at 0° C.
- (b) One cell (average capacity) to be tested at 25° C.
- (c) Two cells (one above average capacity and one below) to be tested at 50° C.
- (5) Figures 3 through 9 are graphs summarizing the results of the charging efficiency test series. They show the amperehours obtained on discharge after each of the several charge periods at each of the five rates and three environmental temperatures, for each of the seven cell types.
- (a) At 0° C and 50° C, the curves shown are averages for the two cells of each type tested in each case, while the curves at 25° C represent only one cell of each type.
- (b) It should be emphasized that the horizontal axis represents (specified charge rate) x (hours of charge), and does not take into account the fact that current was reduced whenever a cell reached the 1.50 volt limit on charge.

## d. Discussion of Results.

- (1) From Figure 1, which depicts the results of the charge and discharge voltages versus time test, it appears that at 0° C and 25° C the charge rate had in general little effect on the discharge capacity. At all three temperatures, the effective capacity at the higher discharge rate of c/2 was below that at the c/5 rate by five percent of the cells' acceptance test capacities. At 50° C, however, the higher charge rate resulted in an average loss of an additional five to seven percent of the acceptance test capacity.
- (2) The results of the overcharge test, shown in Figure 2, vary considerably with cell type. At 25° C, all types except the Gulton 6.0 ah and Gulton 20 ah averaged lower stabilizing voltages at the c/l rate than at the c/l0 rate, showing that the increase in cell temperature caused by the increased charge current

had a greater effect on the voltages of these cells than did the charge current itself. All Gulton cells had reached the 1.55 volt limit by the end of the test, with half the cells having reached this limit at the c/10 rate. The other cells which reached the voltage limit were one Gould 20 ah at the c/8 rate, and two Sonotone 5.0 ah and one Gould 3.5 ah at the c/10 rate. At the c/1 rate, three Gould 20 ah cells were removed due to high cell temperatures, and three G.E. 12 ah cells were destroyed by thermal runaway. It is probable that if the cells had been subjected to the c/l rate immediately, rather than being built up gradually a step at a time, they would have exceeded the voltage limit at that rate. At 50° C excessive temperatures occurred among each of the four rectangular cell types. For the Gulton cells, both 6.0 ah and 20 ah types, this first occurred at the c/2 rate; for the G.E. 12 ah and Gould 20 ah cells, excessive temperatures occurred only at the c/l rate. There were no destructive failures at this temperature. The average stabilizing voltage at the c/l rate for the Gould 3.5 ah, the Gould 20 ah and the Sonotone 5.0 ah cells was from 0.06 to 0.09 volts higher than that at the c/10 rate. For all other types, the stabilizing voltage at c/l was approximately the same as or slightly less than at c/10.

- (3) For the charging efficiency tests, it can be observed that the characteristics of the resulting curves (Figures 3 through 9) generally tend to fall into groups according to manufacturer, as outlined below.
- (a) The Gulton cells at 0° C showed relatively little difference from one charge rate to another. At 25° C the maximum output tended to increase with charge rate whenever the charge for that cycle exceeded 75 percent of the cells' rated capacity. At 50° C the output was greatest for the c/l charge rate, and was least for the c/5 rate.
- (b) The results from the G.E. cells are essentially similar to those from the Gulton cells, with the following exceptions: At 0°C the output at the c/l rate continued to increase above those of the other charge rates as the charge period was extended beyond 125 percent of the cells' rated capacities. At 25°C the differences in output between the high and intermediate charge rates were less pronounced although the trend towards higher output for higher charge rate was still apparent.
- (c) The results for both types of Gould cells were quite distinct from those for the Gulton and G.E. At 0° C the output was again fairly independent of charge rate except that at the c/l rate the curve fell considerable below the others over most of its length. All four cells generally reached the 1.50 volt limit after less than one-half hour of charge at these conditions, with

charge current therefore reduced for the remainder of the charge (those cell types which did not show a reduced output for the c/l charge rate at 0° C did not limit until approximately 0.75 hours of charge). At 25° C there was very little separation between the ultimate outputs at the different rates, although for the 20 ah cell the c/l curve falls below the others over most of its length. However, this cell also limited early at these conditions. At 50° C the c/l rate still resulted in the greatest output, but the remaining curves were much closer together so that the c/5 curve is no longer distinct from them.

- (d) The outputs of the Sonotone cells at 0° C showed little dependence on charge rate. At 25° C, as with the Gulton cells, the output tended to increase with charge rate, especially when the charge was extended beyond the cell's rate capacity. At 50° C there is comparatively less separation between the five curves, as compared with those of the other cell types, although the c/5 curve is again the lowest.
- (e) An additional characteristic is that for all cell types at both 0° and 25° C the leveling-off points, or "knees" of the curves usually occur when the cells have been charged to between 100 percent and 150 percent of their rated capacity, whereas, at 50° C such knees are frequently obscure or even absent. In these cases, however, if the curves were to be extended backwards from their starting point at 50 percent of the cells' rated capacity to the point of zero ampere-hours on charge (and, therefore, zero ampere-hours on discharge), it is clear that a sharp downward bend (that is a knee) would have to be made in order to connect the two points. It is therefore probable that at some charge rates at 50° C the knee had already been reached by the time the cells had been charged to 50 percent of their rated capacity, which was the starting point of the test at each rate.
- (4) In some instances the results of the charging efficiency tests were partially borne out by the charge and discharge voltages versus time, but there are some notable exceptions. In both tests there was little difference between the capacities following the c/10 and c/5 charge rates at 0°C, with the exception that in the first test the output of the Sonotone cells averaged five to ten percent higher following the c/10 rate, but in the charging efficiency test averaged virtually no difference. A greater difference is found at 25°C, however. In the charge and discharge voltages versus time tests, the cells were charged to 160 percent of their rated capacity (for example, a 32 ampere-hour charge for the 20 ah cells). From investigation of this point on the charging efficiency graphs, it would seem that the G.E. 12 ah, both types of Gulton cells, and to some extent the Gould 3.5 ah cells would have shown a higher output following the c/5 charge rate, on the first test (Figure 1), than

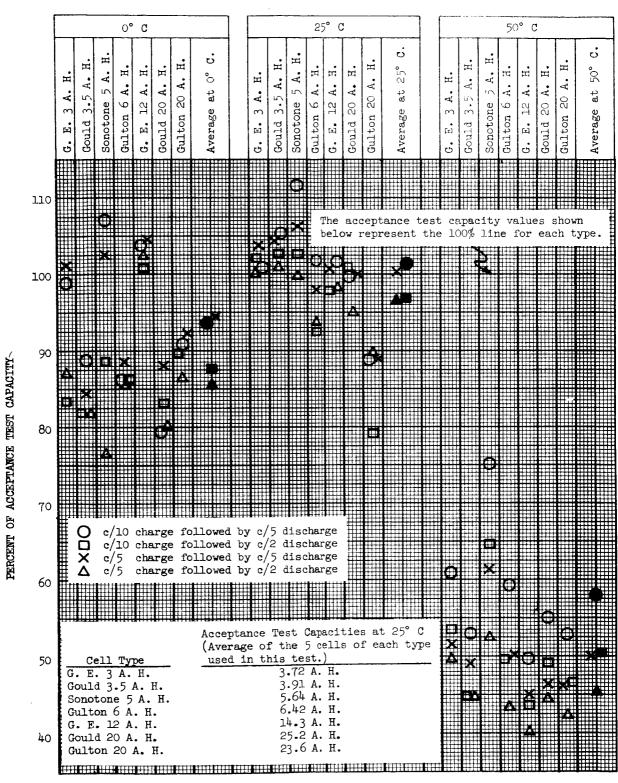
that following the c/10 rate. For all types except the Gulton 20 ah this is not the case, the output after charging at c/10 being the same or slightly higher than that after charging at the c/5 rate. It is not clear whether these differences are due to the test procedures, a natural variability in the cells, or a change induced in the cells by the tests. At 50°C there is good agreement, in that the c/10 charge rate almost invariably resulted in a greater discharge capacity at the point of 160 percent recharge than did the c/5. Possible exceptions to this were the Gould 3.5 ah cells, but in this case the c/10 rate on the charging efficiency test was not extended as far as the 160 percent recharge. However, the fact that in Figures 3 through 9 the average output for the c/5 charge rate is persistently out of sequence with those for the other rates at this temperature for all but the two types of Gould cells suggests an anomaly at this rate.

TABLE III

## ACCEPTANCE TEST CAPACITIES AND

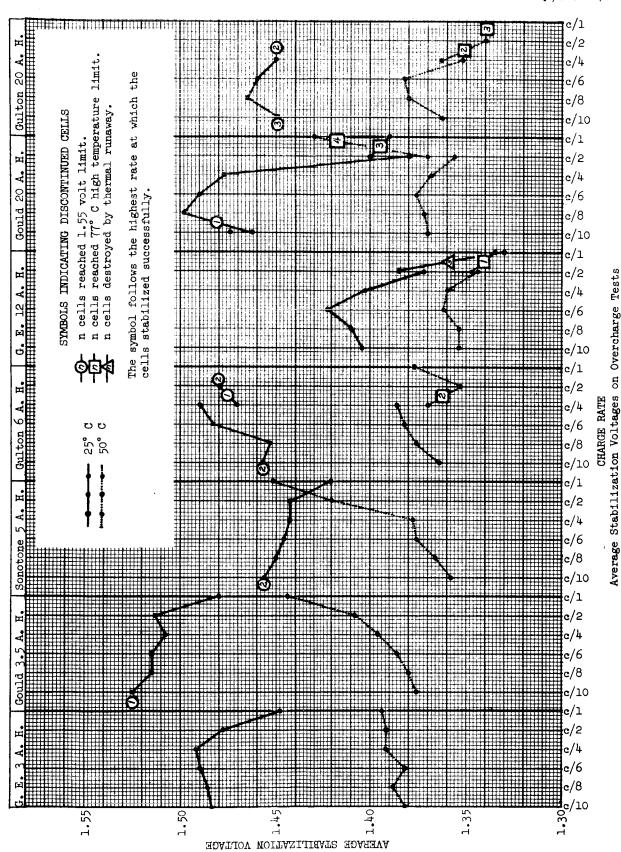
CHARGE AND DISCHARGE VOLTAGE VERSUS TIME CAPACITIES (Averages of the Same Five Cells of Each Type)

Charge and Discharge Voltage vs Time Capacities Acceptance Test Ambient c/10 O c/5 **X** c/10 C Capacities @ Temp. Charge @: <u>c/</u>2 **Δ** Cell Type °C 25° C (ah) Discharge @: G.E. O° C 3.68 3.76 3.10 3.23 25° C 3.0 ah 3.72 3.75 3.86 3.80 3.72 50° C 2.26 1.92 1.99 1.85 Gould 0° C 3.47 3.30 3.20 3.20 25° C 4.12 3.5 ah 3.91 4.08 4.01 3.94 50° C 2.07 1.92 1.75 1.75 0° C 25° C 50° C Sonotone 6.03 5.78 5.00 4.32 5.0 ah 5.64 6.30 5.62 5.99 5.79 4.24 3.46 3.65 2.96 0° C 25° C 50° C Gulton 5.55 5.70 5.55 5.50 6.42 6.0 ah 6.30 6.55 6.03 5.95 3.80 3.18 3.22 2.78 O° C G.E. 14.85 14.90 14.40 14.65 25° C 12 ah 14.30 14.55 14.40 14.00 14.05 5.75 7.10 6.45 6.25 0° C 25° C 50° C Gulton 21.45 21.80 21.18 20.40 20 ah 23.62 21.00 21.05 18.70 21.20 12.50 10.90 11.00 10.00 O° C Gould 20.00 22.20 20.95 20.20 25° C 20 ah 25.20 25.15 25.23 25.45 23.95 50° C 13.87 11.66 12.40 11.18

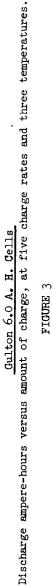


Discharge Ampere-hours Under Specified Parameters Expressed as Percentage of Acceptance Test Capacities

FIGURE 1



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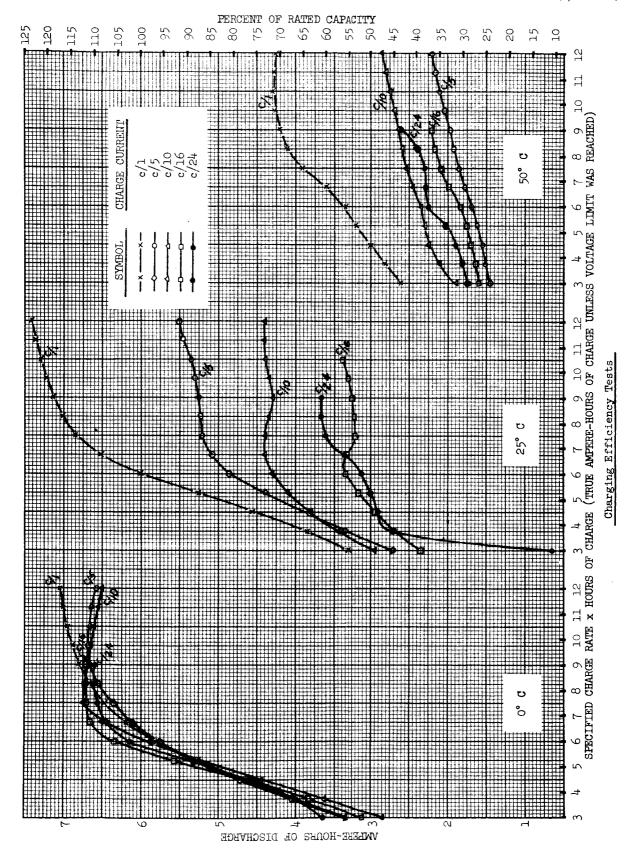
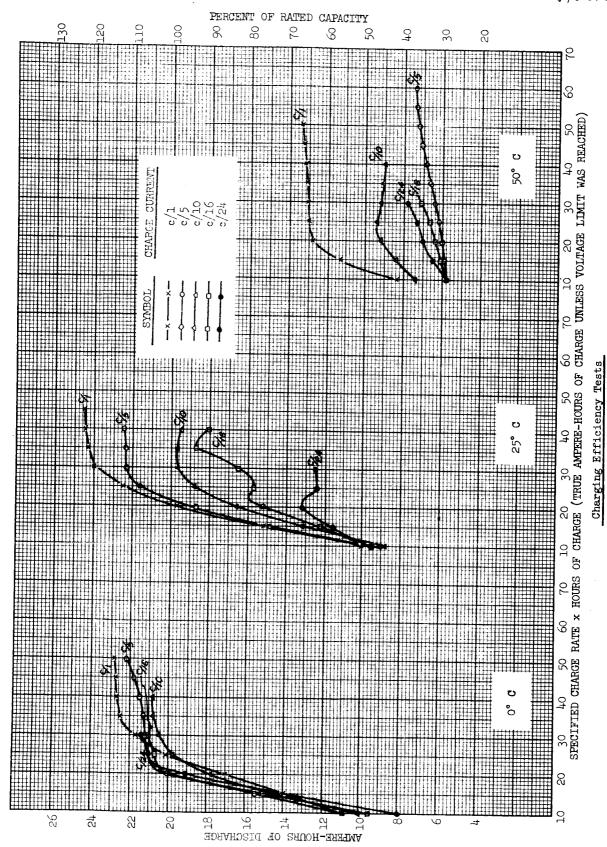
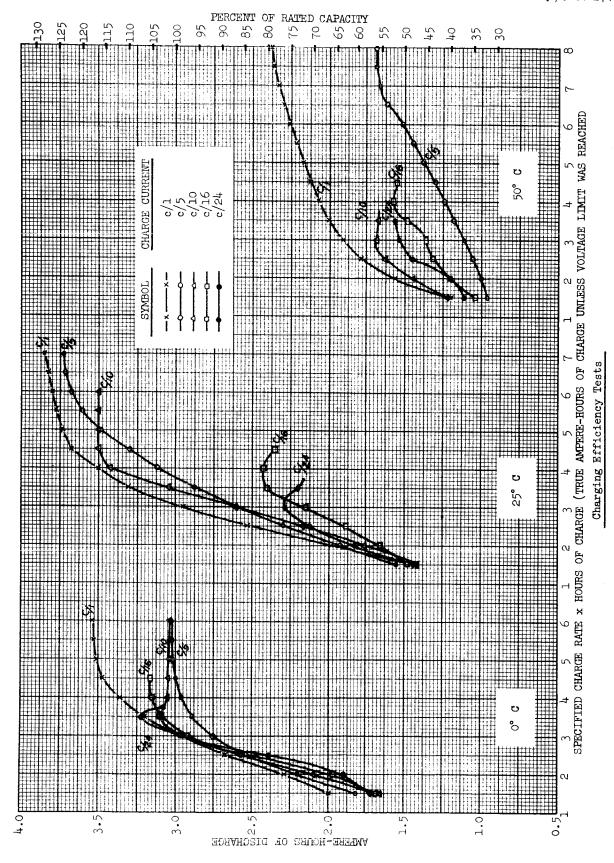


FIGURE 4

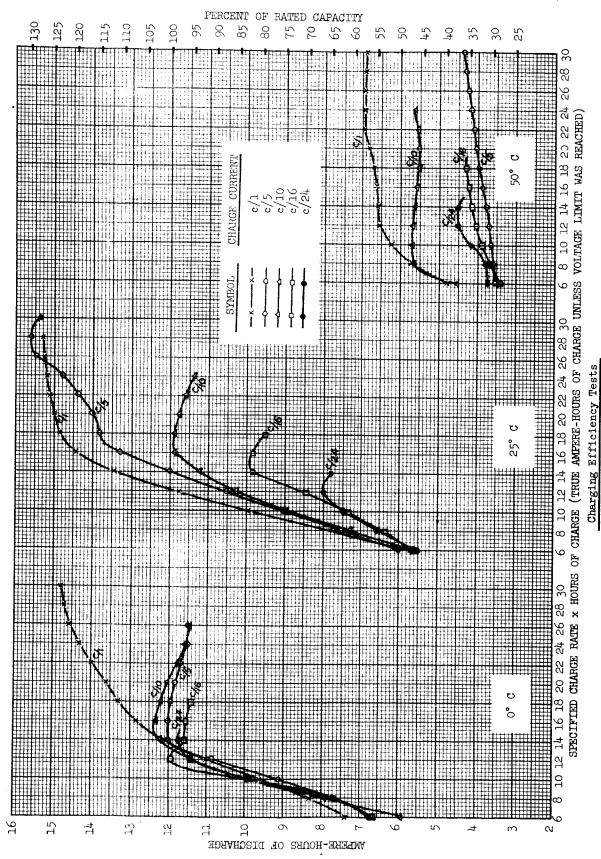


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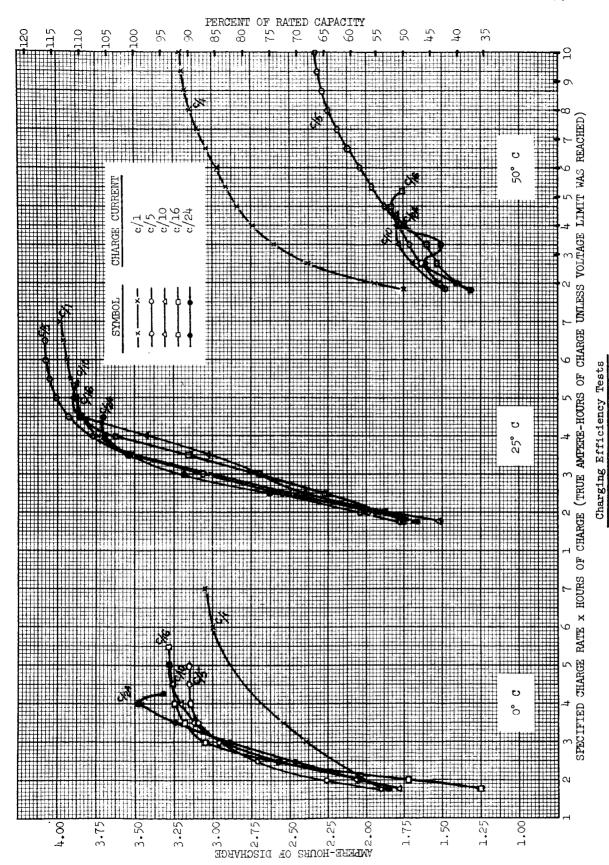
Discharge ampere-hours versus amount of charge, at five charge rates and three temperatures.



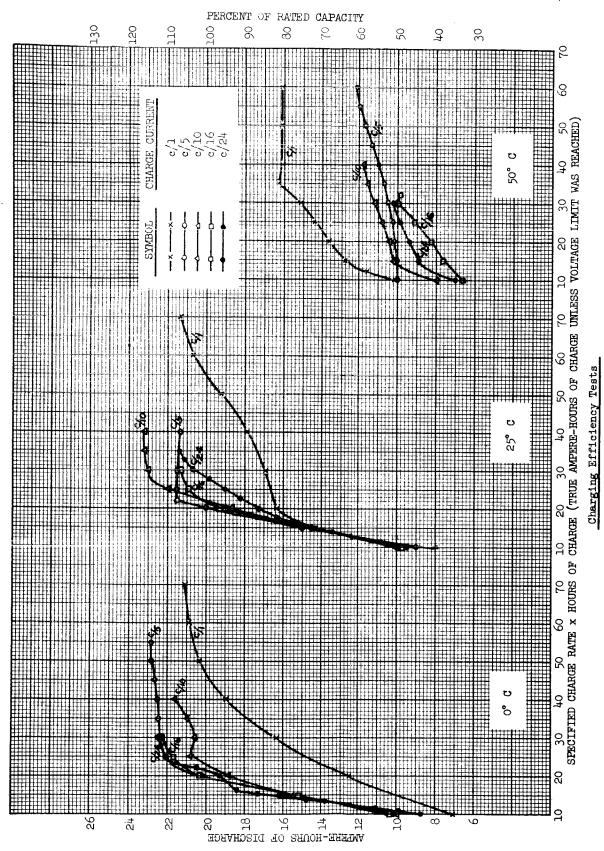
22



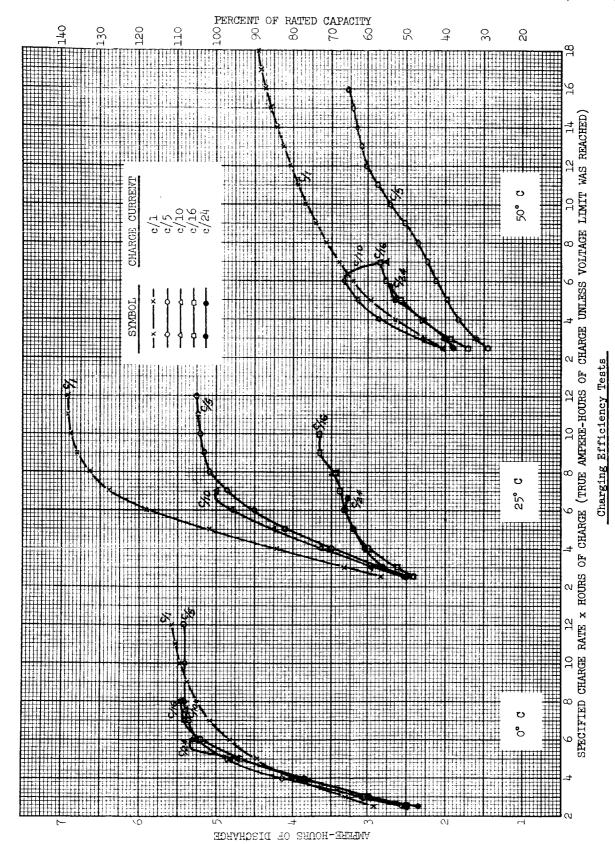
G. E. 12 A. H. Cells Discharge ampere-hours versus amount of charge, at five charge rates and three temperatures.



Gould 3.5 A. H. Cells
Discharge ampere-hours versus amount of charge, at five charge rates and three temperatures.



Discharge ampere-hours versus amount of charge, at five charge rates and three temperatures.



Sonotone 5.0 A. H. Cells Discharge ampere-hours versus amount of charge, at flve charge rates and three temperatures.

## V. TEST FACILITIES.

- A. Environmental Chambers: Ambient test temperature conditions were obtained with the following equipment.
- 1. 0° C. Cell packs cycling at 0° C are in a 27 cubic foot chamber manufactured by the A. Webber Engineering Corporation, Model WF-27-40. The temperature controls are accurate to within  $\pm$  1.5° C.
- 2. 25° C. Packs cycling at 25° C are located in an air conditioned room with other temperature critical equipment. The temperature is maintained at  $25 \pm 2^{\circ}$  C.
- 3.  $40^{\circ}$  C. Packs cycling at  $40^{\circ}$  C (started at  $50^{\circ}$  C) are in a 27 cubic foot chamber manufactured by Missimers, Incorporated, Model FT 27 X 300. The temperature controls are accurate to  $\pm$  1.5° C.

## B. Charge and Discharge Control Units.

- l. Each cell pack is connected to its own, independent, solid state current limiting charging unit. These units control the charge rates and voltage limits by regulating the current supplied by a 28 VDC generator which is common to all units. They also discharge the packs by a relay switching system which changes the current lead connections within the units. Each has two ammeters rated at ± 1 percent accuracy for visual monitoring of charge and discharge currents, and three separate controls for setting the currents and voltage limit at the desired values. A 3-position switch selects between continuous charge, continuous discharge and automatic cycling operation. Automatic cycling is controlled by 90-minute and 3-hour synchronous motor timers, each of which is common to all corresponding units through a relay switching system. Reference voltages for the voltage limiting circuits are supplied by small transformer DC power supplies from a regulated 117 volt AC source.
- 2. Photograph 2 shows a front view of several charge-discharge units. Figure 10 is a schematic diagram of a typical charge-discharge unit.

## C. Upper and Lower Voltage Limit Monitoring System.

- l. Each pack is connected to its own lower limit voltmeter which sets off an alarm common to the system and turns on an identifying light for the particular pack when the terminal voltage of the pack falls below a present limit. Photograph 3 is a picture of the Lower Voltage Limit Monitoring System.
- 2. To be added is a system which will scan each individual cell voltage. When the voltage of any cell is found to be outside the preset upper and lower limits, the system will automatically set

off the preset alarm, and will also disconnect the current leads of that pack by de-energizing a relay. The system will include a scanner, a DC to frequency converter and a frequency counter, and will scan each cell every 2 minutes.

# D. Data Logging System.

# 1. Brief Summary.

a. Recordings are made by means of a data logging system (Photograph 4) obtained from Gulf Aerospace Corporation. All monitoring leads from a given pack of cells are scanned, converted to digital form and fed to the Tally Mark 45P paper tape punch and programmed reader. The system permits the current, pack terminal voltage, all cell voltages and thermocouple voltages for a given pack to be read and punched out within less than 4 seconds. An additional switching arrangement permits recording up to six 10-cell packs and 12 5-cell packs at one time.

# 2. Technical Description.

- a. This system is designed to record data from 30 data channels by sampling and scanning the input voltages. The data is converted to binary code by a precision amplifier and a high speed analog to digital converter and is presented serially by character to the paper tape punch for storage of the data. Figure 11 is a block diagram of the data logging system.
- b. The system measurements are either timed and controlled by the system's digital clock, or manually controlled by the operator. Additional features of the system provide for a typed report of the stored data.
- c. The system has 30 input channels. Of these, channels 1 to 10 have a full scale input of 10 volts and measure battery cell voltages. Channels 11 and 13 have a full scale range of 20 volts and measure the total pack voltages. Channels 12 and 14 have a full scale range of 100 millivolts and measure the voltage across 100 millivolt current shunts.
- d. All of these inputs, 1 to 14, are sample and hold type inputs. They are sampled simultaneously for 400 milliseconds. The attenuated input signal voltages, all of which are normalized to 100 millivolts full scale, are stored on high quality capacitors. The scanner then sequentially scans these capacitors for data readout. This technique is used to eliminate any difference in time between the first 14 input readings. The accuracy of these channels is  $\pm$  0.25 percent of full scale reading.

- e. Channel 15 is used for battery pack identification. Another instrument, which provides selection for monitoring a given pack from a group of packs, provides an output from which the particular pack selected can be identified. This output voltage is read on channel 15 as the position identifying the pack. The operator or project leader correlates these readings with specific packs being tested.
- f. Channels 16 through 30 are low level input channels ( $\pm$  10 millivolts full scale) designed to monitor thermocouple inputs with an accuracy of  $\pm$  1 percent of full scale. These channels have a maximum common mode voltage that can exist between the signal and the system ground of  $\pm$  10 volts. If the common mode voltage exceeds this value, accurate readings can no longer be taken. (Common mode voltages of over  $\pm$  20 volts may damage the differential amplifier.)
- g. Cycle time for this system is less than 4 seconds for all 30 channels. The readout system, a Tally Mark 45P, is capable of receiving data from the analog to digital converter, from a prepunched paper tape, or from the Selectric typewrite by manual input and may be programmed to print out the data, off line, in any desired format.

# 3. System Operation.

- a. During the scanning process each channel in turn is routed to the input of a high impedance differential amplifier, the gain of which is automatically switched between 100 (the amount used for the high level channels) and 1000 (the amount required for the low level channels). The sensing for the gain change is supplied by the relay drivers. Provisions are made to eliminate amplifier drift while sampling voltage across the storage capacitors. The output of the amplifier is applied through a low pass filter at the input of the analog to digital converter. The analog to digital converter is then given a command to read.
- b. The analog to digital converter converts the analog signal to a binary coded decimal signal. A serializer sequentially sends one digit at a time from the output of the clock or from the analog to digital converter to the perforator driver. The zero generator and the parity generator maintain the proper digital format for punching paper tape and operating the Selectric typewriter in the Tally Mark 45P system. The punched-paper-tape code is compatible with IRM binary coded decimal code (Hollerith).

# 4. System Controls.

a. The 30 position Data Scanner has several modes of operation. Mode switch may be set to continuous cycling, preset cycle, single cycle, single step, and manual select. In the continuous cycling position the scanner continues to sample the data at a

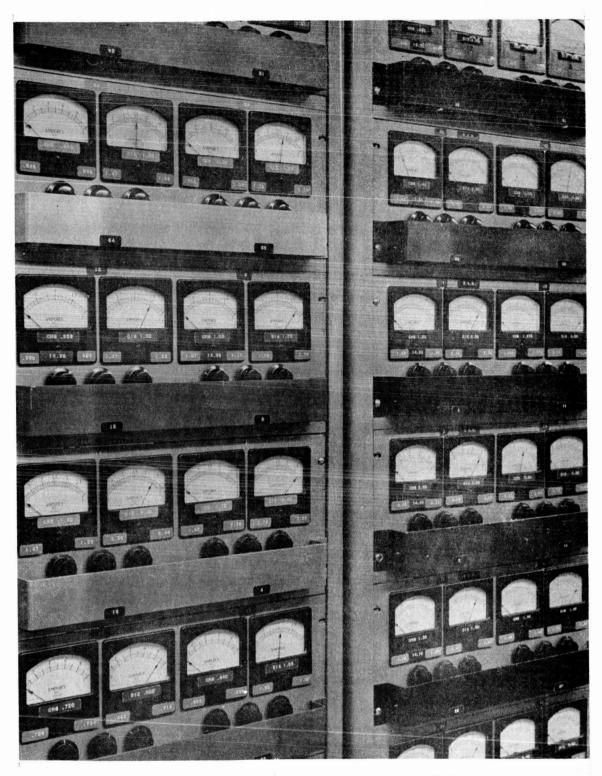
rate determined by the digital clock. In the preset cycle position the scanner takes a sample of the data at a time determined by the preset time selector. In the single cycle position the scanner samples the data once each time the step/cycle push button is depressed. In the single step position the scanner is advanced one channel at a time by depressing the step/cycle push button switch. In the manual select position the scanner remains at the channel selected by the manual select switches. When in either of the two manual modes a reading is taken by pushing the print button. The scanner has two front panel displays, one for channel number and one for voltage. All system functions are timed by a unijunction oscillator and are controlled by logic circuits in the scanner assembly.

# E. Central Wiring Panel.

1. All electrical connections are made through a centrally located wiring panel which houses the current shunts and a plug-in panel. Photograph 5 shows the front view of the central wiring panel.

#### F. Pack Selector Switch.

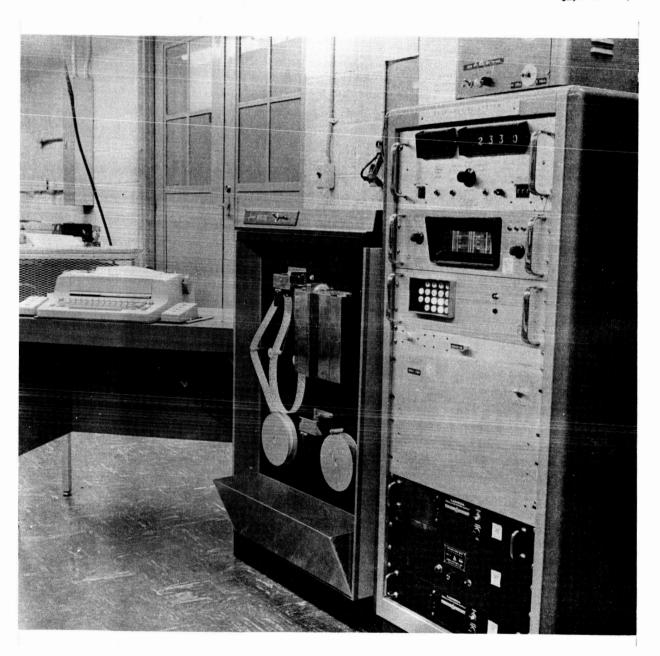
- 1. Up to six 10-cell packs and 12 5-cell packs may be plugged into a selector system from the central wiring panel. Through reed relays operated by a selector switch, any of these packs can then be connected to the input of the Data Logging System. This arrangement allows all currents and cell and thermocouple voltages for all 18 packs to be recorded by the Data Logging System within 48 seconds.
- 2. The switching system also provides a voltage which identifies the selected position and which is automatically recorded as part of the data for the pack selected.
- 3. Photograph 4 shows the pack selector switch located on top of the Data Logging System.
- G. Block Diagram of Entire Test Setup. Figure 12 shows the arrangement from the packs at each of the three ambient temperatures to the central wiring panel. Leads from the central wiring panel connect all packs and/or cells to the charge-discharge units and the 28 volt DC source, the circuit relay switching system, the voltage limiting monitoring system and the data logging system.
- H. Photograph of Test Area. Photograph 6 shows the overall arrangement of the test equipment described in paragraphs V.B. through V.G.



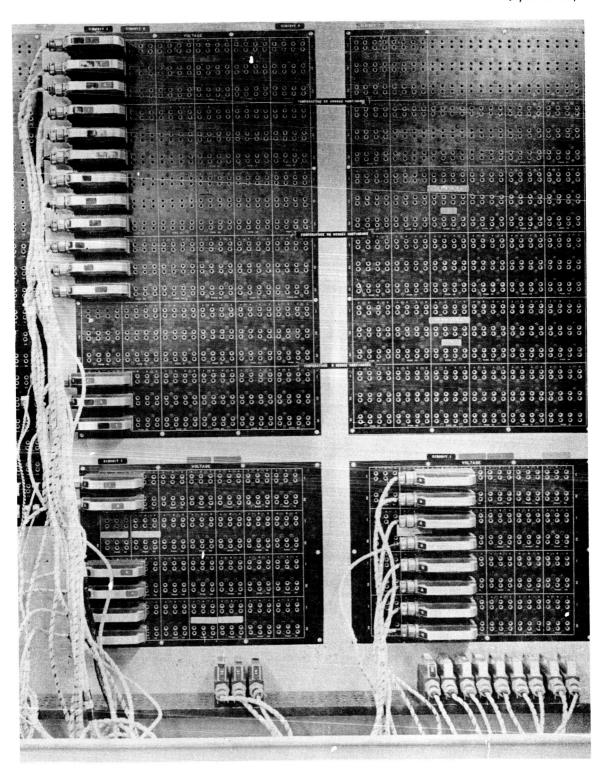
Several Charge and Discharge Control Units F:OTOGRAPH 2



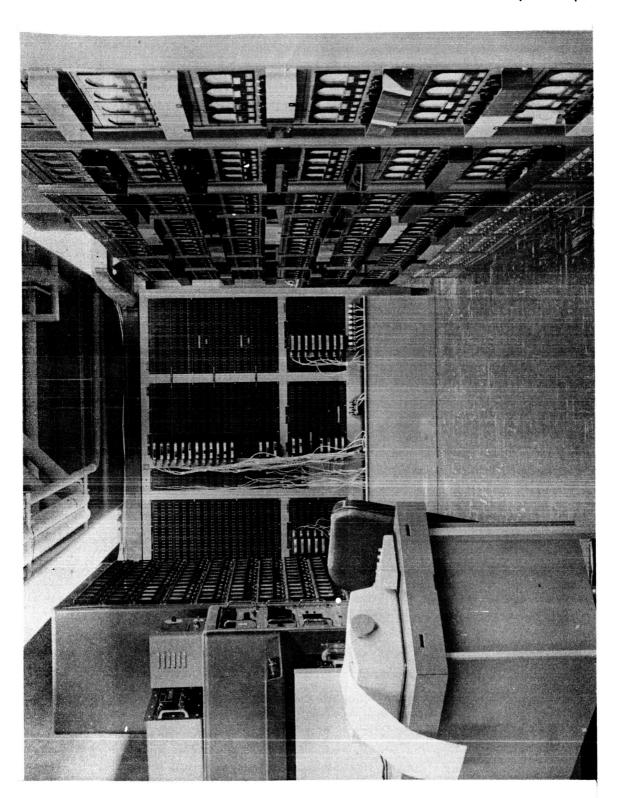
Voltage Monitoring Panel PHOTOGRAPH 3



Data Logging System
PHOTOGRAPH 4



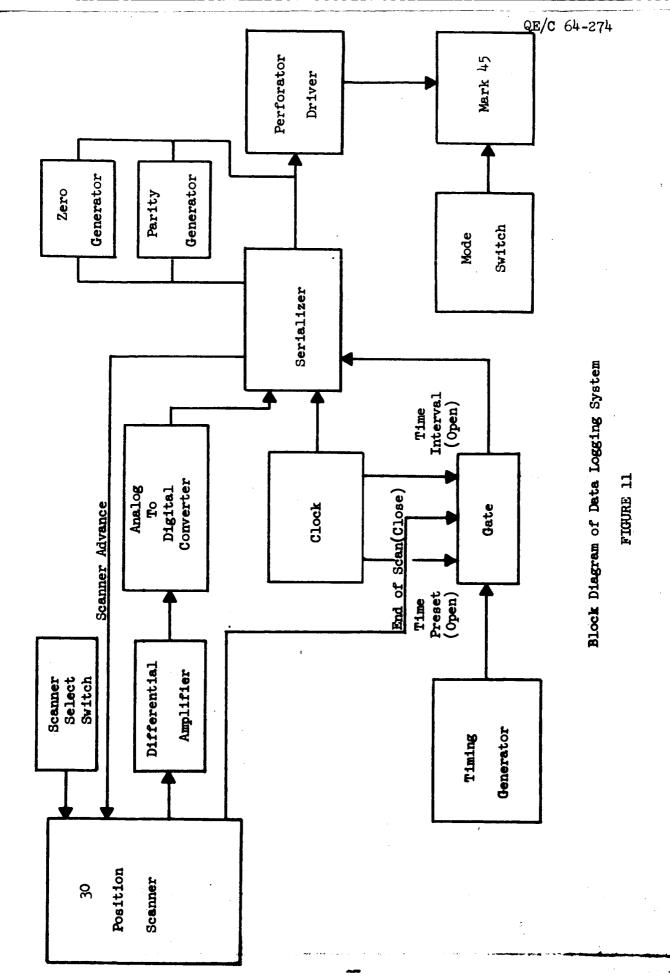
Portion of Central Wiring Panel PHOTOGRAPH 5

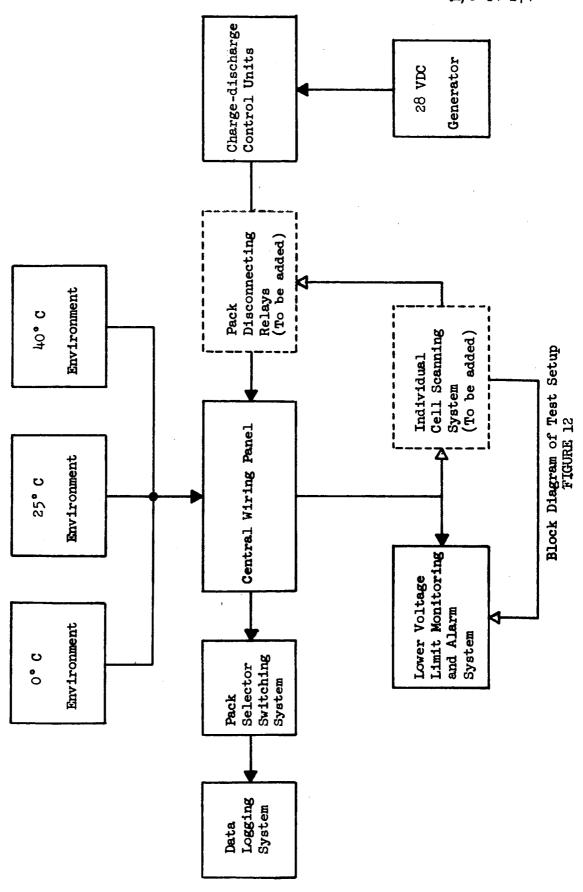


Schematic Diagram of a Typical Charge-Discharge Unit

FIGURE 10

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VI. CYCLING TESTS. Following completion of the general performance tests, a total of 660 cells (84 packs), subjected only to the acceptance tests, were prepared for the cycling tests.

# A. Preparation of Cells.

- l. Pack Arrangement. The cells of each manufacturer type were connected in series into 5-cell or 10-cell packs. Within each pack, the cells were given numbers from 1 to 5 or from 1 to 10, for identification of their relative electrical and physical positions. These are shown in Figure 13.
- a. General Electric Company 3.0 Ampere-hour (10-cell Pack).
- (1) Each cell was wrapped in a double layer of 0.003 inch polyethylene sheet and arranged into oval shaped packs held together with tape, according to diagram (a) of Figure 13. The electrical leads were soldered to the terminals on the top of the cells. The cells are cycling in the vertical position.
- b. Gould-National Batteries, Inc. 3.5 Ampere-hour (10-cell Pack).
- (1) Each cell was wrapped in a double layer of 0.003 inch polyethylene sheet and arranged into triangular packs held together with tape, according to diagram (b) of Figure 13. The pigtail lead extending from the center of the top is the negative terminal. Since the case is positive, a tab was soldered to the base of each cell. The series electrical connections were made by soldering the pigtail negative terminal lead of one cell to the tab at the base of an adjoining cell. The cells are cycling in a horizontal position.
  - c. Sonotone Corporation 5.0 Ampere-hour (10-cell Pack).
- (1) Each cell was wrapped in a double layer of 0.003 inch polyethylene sheet and arranged into oval shaped packs held together with tape, according to diagram (c) of Figure 13. The electrical leads were soldered to the terminals on the top of the cells. The cells are cycling in the vertical position.
- d. Gulton Industries, Inc. 6.0 Ampere-hour (10-cell Pack).
- (1) The cells were arranged in line between two 1/4 inch steel plates and held together with four 1/4 inch steel bolts, as in diagram (d) of Figure 13. The cells were insulated from each other and from the end plates by a layer of 0.015 inch insulating paper between two layers of 0.003 inch polyethylene sheet.

The electrical leads were soldered to the terminals on the tops of the cells. The cells are cycling in the vertical position.

- e. General Electric Company 12 Ampere-hour (5-cell Pack).
- (1) The cells were arranged in line between two 1/4-inch steel plates and held together with four 1/4-inch steel bolts. The cells were insulated from each other and the end plates by a layer of 0.015 inch insulating paper between two layers of 0.003 inch polyethylene sheet. The electrical connections were made at screw terminals on the tops of the cells. The cells are cycling in the vertical position.
- f. Gould-National Batteries, Inc. 20 Ampere-hour (5-cell Pack).
- (1) The cells were arranged in line between two 1/8-inch steel plates and held together with four 1/4-inch steel bolts. The cells were insulated from each other by a double layer of 0.003 inch polyethylene sheet. The electrical connections were made at the screw terminals on the tops of the cells. The cells are cycling in the vertical position.
  - g. Gulton Industries, Inc. 20 Ampere-hour (5-cell Pack).
- (1) The cells were arranged in line between two 1/4-inch steel plates and held together with four 1/4-inch steel bolts. The cells were insulated from each other and from the end plates by a double layer of 0.003 inch polyethylene sheet. The electrical leads were soldered to the terminals at the tops of the cells. The cells are cycling in the vertical position.

#### 2. Temperature Monitoring.

- a. A thermocouple (Iron-Constantan, type J) was soldered to the positive terminal of each cell under test.
- (1) In the Gould 3.5 ampere-hour cells, the case being the positive terminal, the thermocouple was soldered to the tab previously soldered to the base of the cell.
- (2) Thermocouple voltages were read simultaneously with cell voltages.
- 3. Preconditioning of Test Cells. Prior to the start of the cycling program, all packs were preconditioned at their designated cycling temperatures as described below. In each case, the on charge voltage limit was the same as set for the cycling program.

- a. After all packs were discharged at the c/2 rate, the cells were equalized to zero voltage by short circuiting across their terminals. They were then recharged at the c/10 rate for 24 hours, except packs of Gulton cells which, in accordance with the manufacturer's recommendations, were recharged at the c/40 rate for 40 hours. This recharge was followed by a discharge at the c/2 rate to a cutoff of 1.0 volt per cell average or to a low of 0.5 volt on any one cell, whichever occurred first. The packs were then recharged at the c/10 rate for 16 hours and discharged at the c/2 rate to the above cutoff point. Any cell showing a significantly low capacity on this second discharge, which would limit the pack's performance on cycling, was replaced and the second charge and discharge repeated on the entire pack.
- (1) The ampere-hour capacities of the last preconditioning cycle are given in Table IV.
- (2) Immediately before the start of cycling, each pack was given a 24-hour charge at the c/10 rate.
- b. Change from 50° C to 40° C ambient temperature. The packs which were changed from the 50° C to the 40° C ambient temperature were preconditioned again, at the lower temperature. They were first discharged beyond the normal cutoff voltage and the cells equalized to zero voltage by short circuiting across their terminals. Each pack was then recharged for 24 hours at the c/10 rate with the pack voltage limited to an equivalent of 1.41 volts per cell. The packs were then discharged according to the original preconditioning procedure, with the exception that cells showing low capacities were not replaced.
- (1) The ampere-hour capacities on this discharge are given in Table IV.
- (2) Immediately before the start of cycling at 40° C each pack was given a 24-hour charge at the c/10 rate.

### B. Test Procedures.

- l. Frequency of Data Recording. The individual cell and pack voltages, currents, and individual cell and ambient temperatures for each measured cycle are recorded at the following designated intervals.
- a. During Charge. The readings during the charge period of the 90-minute orbit were taken at the beginning and end of charge and at 10-minute points between, whereas during the 3-hour orbit, readings were recorded at the start and end of the charge period and at 20-minute points between.

- b. During Discharge. The readings during the discharge period of both the 90-minute and 3-hour orbit periods were taken at the beginning and end of the discharges and at 5-minute points between.
- c. Measured cycles were normally the first cycle and approximately every 32 cycles thereafter. This data was also recorded whenever a possible cell failure or pack failure was indicated.
- 2. Data Processing. The data is typed on continuous form paper while succeeding readings are recorded on punched tape. The data is then converted to 5081 Data Processing Cards and stored according to pack and cycle number.
- 3. Cell Failures. Cells were removed from their respective packs after it had been shown that they had failed.
- 4. Capacity Checks. The ampere-hour capacity of each pack, in its specified ambient temperature, was measured after completion of each 88 days of continuous cycling. This is equivalent to approximately every 1400 cycles for the 90-minute orbit periods and every 700 cycles for the 3-hour orbit periods.
- a. During the capacity checks, the on charge voltage limit was the same as for cycling. Each pack being checked was discharged immediately after the end of the regular cycle charge period, at the c/2 rate to a cutoff of 1.0 volt per cell average or to a low of 0.5 volt on any one cell, whichever occurred first. The pack was then recharged at the c/10 rate for 16 hours and discharged again as above. For those packs which had completed 88 days of cycling as of this report, the ampere-hours delivered on both discharges are given in Table IV.
- b. Before being returned to regular cycling, the pack was given a 48-hour charge at the c/10 rate, with the regular cycling voltage limit on charge.

# C. Cycle Life Test Results.

- 1. Presentation of Results. The cycle life test results are presented in a series of tables and graphs as noted below:
- a. Table V gives the number of cycles completed by 31 March 1964, the end of the first quarterly period of the cycling program, for each cell type under each test condition.
- b. Table VI lists the cell failures which occurred during the first quarterly period of the cycling program, showing for each cell the types of failures, the test conditions under which it was

cycling and the number of cycles it completed before failing. Each cell is identified both by the manufacturer's serial number and by its position in the pack (as shown in Figure 13). Table VII is a summary giving only the total number of failures for each cell type under each of the test conditions.

- c. Table VIII gives a typical temperature range during discharge and during charge for each of the 84 packs being cycled. This temperature data is from the thermocouple readings taken during the last month of the first quarterly period of the cycle program.
- d. Figure 14 is a typical set of characteristic voltage curves for three 10-cell packs of the same cell type, all on a 90-minute orbit period and at 25 percent depth of discharge, but with one pack at 0° C, one at 25° C, and one at 40° C.
- e. Figures 16 through 99 show the voltage at 15 minutes and at 30 minutes of discharge plotted against cycle number for each pack.
- (1) Points are plotted at intervals of approximately 100 cycles in the case of the 90-minute orbit period, and of approximately 60 cycles for the 3-hour orbit period.
- (2) The information on Figures 16 through 99 also includes, for each pack: The average voltage of active cells plotted against cycle number, the number of cell failures up to any given time, the points at which failures occurred, and other events which may be of interest in evaluating the results.
- (3) Figure 15 is an example of the various lines shown in Figures 16 through 99 with explanations of their meanings. The points connected by a heavy, solid line represent the pack terminal voltages and refer to the left-hand vertical scale, while the small x's connected by a dotted line represent the average voltage of the remaining, active cells for the same points during the discharge and refer to the right-hand vertical scale. Invariably, the upper line of each pair represents the voltage at 15 minutes, and the lower line represents the voltage at 30 minutes.
- (4) The absence of a connecting line between two points indicates that on some cycle in that interval either a cell failed and was removed or a change was made in the environmental temperature. These and all other events which are related to the cycling history of each pack are also indicated on each graph by a number which refers to an explanatory note below the graph.
- (5) An additional heavy, horizontal line at the top of the graph represents the number of cells which have failed.

Initially it is slightly above the top of the graph, indicating no failures in that interval. Thereafter, the line drops one division at each cell failure. The procedure is the same for both 5-cell and 10-cell packs, so that the line is not a direct indication of the number of cells in the pack.

(6) The graphs are arranged in groups according to cell capacity, and within each group according to temperature, as shown below:

G.E. 3.0 ah Packs

Temperature	Percent Depth of Discharge	Orbit Period (Hours)	Figure Number
o° c	15	1.5 3	16 17
	25	1.5 3	18 19
25 <b>°</b> ¢	25	1.5 3	20 21
	40	1.5 3	22 23
50° - 40° C	15	1.5 3	24 25 26
	25	1.5 3	26 27

Gould 3.5 ah Packs
Sonotone 5.0 ah Packs
Gulton 6.0 ah Packs
G.E. 12 ah Packs
Gould 20 ah Packs
Gulton 20 ah Packs
Figures 28 - 39
Figures 40 - 51
Figures 52 - 63
Figures 64 - 75
Figures 76 - 87
Gulton 20 ah Packs
Figures 88 - 99

### 2. Discussion of Results.

a. Cell Failures (Tables VI and VII). In considering cell failures it should be noted that the specified charge rates in the cycling program usually exceed the maximum rates recommended by the manufacturers. For example, packs which are cycling in a 90-minute orbit at 25° C with a 40 percent depth of discharge are being charged at the c/2 rate, although none of the manufacturers recommend charge rates greater than c/10. The only charge rate below c/10 is that for the 3-hour, 15 percent depth of discharge, 0° C (115 percent recharge) combination, for which the charge rate is c/14.5. Failures will be discussed according to manufacturer.

- (1) General Electric Company.
- (a) 3.0 ah cells. One failure. No failure analysis has been made on this cell to date.
  - (b) 12 ah cells. No failures.
- (2) Gould-National Batteries, Inc. All failures of Gould cells were analyzed by a representative of the manufacturer.
- (a) 3.5 ah cells. Seven failures. Six of the seven showed leakage at the glass-to-metal seal at the negative terminal, and had weight losses of from 1.5 to 3.5 grams. The remaining cell showed internal corrosion deposits on the negative terminal. This cell also showed a weak weld where the tab of the positive plate was welded to the cell case. This weld in one of the other six cells was questionable. Both cells were shorted internally. A third cell had a foreign particle on the separator material, and a short developed through the separator at that point. This cell and two others developed high internal pressure and were bulged at one or both ends of the case. All but one of the failures were at the 50° and 40° C temperatures. All failures were at the greater depth of discharge for their environmental temperatures.
- (b) 20 ah cells. One failure. This cell had been cycling at 25° C in a 3-hour orbit, with a 40 percent depth of discharge, and had developed a short through the separator.
- (3) Gulton Industries, Inc. Initial failures were analyzed by a representative of the manufacturer. The remaining failures were analyzed by NAD Crane personnel, by direction of the manufacturer.
- (a) 6.0 ah cells. Sixteen failures. Eleven of these cells showed weight losses of from 3 to 12 grams. Only four of these showed any evidence of leakage deposits at the terminals or case welds. A total of eight of the cells had built up a conductive deposit across the ceramic seal, inside the cell, which eventually shorted the positive terminal to the negative case. Six cells had bulged due to high internal pressure. One of these and two others were concave on the sides due to the greater pressure of the adjacent cells in their packs, and in one of them the side had been pressed in until it shorted against the positive plate bus. The two cells which failed almost immediately at 0° C had shown no evidence of malfunction during preconditioning. These were replaced and the failures were not included on the graph for that pack.
- (b) 20 ah cells. Seven failures. Four of the cells were from one pack (90-minute orbit, 25° C, 40 percent depth of discharge), making this the only pack failure of the first quarter.

Of the seven failed cells, five showed weight losses of from 8 to 26.7 grams, although only two of these showed evidence of leakage deposits. Two of the seven exhibited the ceramic short discussed for the 6.0 ah cells. In these cells, both the positive and negative terminals are insulated from the case by ceramic seals, and although the short to the case was at the positive terminal in both cases, smaller deposits of the same type were noted at the negative terminals. Four cells were bulged by high internal pressure. The walls of one cell were concave due to the higher pressure of the adjacent cells in its pack, and one wall had been pressed in until it shorted across the positive and negative busses inside the cell.

- (4) Sonotone Corporation. No failures.
- b. Cell Temperatures.
- (1) The temperature ranges shown in Table VIII are readings from the thermocouples soldered to the positive terminals of the cells. The temperatures in each case are the maximum for any cell in the pack, and the minimum for any cell in the pack.
- (2) At 25° C the cells are exposed directly to the moving air of the room. The midpoint of the temperature range at the positive terminals is usually from 5° to 10° C above ambient. Generally, for each type, the packs at the 40 percent depth of discharge show temperatures 3° to 5° C higher than those at the 25 percent depth, and at each depth the range for the 90-minute orbit is slightly higher than for the 3-hour orbit.
- (3) At 0° and 40° C the thermocouples are exposed to the rapidly moving air in the temperature chambers, which may account for the fact that the differences which had been observed at 25° C are less apparent. Thermocouple temperatures in the 0° C environment average 1° to 2° C above ambient, with the maximum temperature rise (8° to 9° C) being shown by the two Gould 20 ah packs cycling at 90 minutes. The majority of packs in the 40° C environment showed almost no rise in average thermocouple temperature above ambient. This is also true for the three packs which were still cycling in the 50° C environment at that time. The maximum temperature rises noted at 40° C were for the Sonotone 5 ah and G.E. 12 ah packs operating at the 25 percent depth of discharge and 90-minute orbit, to 48.9° and 47.3° C respectively.
  - c. Packs held at 50° C.
- (1) Of these four, the G.E. 3.0 ah and Gould 3.5 ah packs were changed to the 40° C ambient after 1440 and 495 cycles respectively, due to a loss of ampere-hour capacity by the G.E. pack (Table IVa) and a cell failure in the Gould pack (Figure 39).
- 3. It is felt that further analysis of results would be premature since the information obtained during the first quarter is incomplete or present in insufficient quantity.

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS G.E. 3.0 ah PACKS TABLE IVa

				(
Third 88 Days	Second Discharge			
Third	First			
Capacity Checks Second 88 Days	Second Discharge			,
Capac 1t Second	First Discharge			
First 88 Days	Second Discharge	5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5. 5	3.70 2.75 3.00	1,92 0,88** 1,35
First	First Discharge	3.25 3.35 3.35 3.35	3.78 2.37 2.98	2.10 0.73** 1.17
Preconditioning	At 40°C*	1		2.43 (779) 2.63 (320) 2.50 (1440) 2.00 (327)
Precon	Initial	3.48 3.63 3.50	4.00 4.03 3.93 78	1.65 1.80 1.60
_	Period (Hours)	1.5	1,5 3 1,5	1.5
Percent	Depth of Discharge	15 15 25 25	25 40 40 40	15 15 25 25
Ambient	Temp.	0000	25 25 25 25	50/40 50/40 50/40 50/40

\* Number in parenthesis indicates number of cycles completed at 50° C. \*\* Pack was still at 50° C when the capacity check was made.

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS GOULD 3.5 ah PACKS TABLE IVD

Third 88 Days	Second Discharge			
Third	First Discharge			
Capacity Checks Second 88 Days	Second Discharge	•		
Capacit Second	First Discharge			
First 88 Days	Second Discharge	3.59 3.85 3.91	4.03 3.38 3.65	1,93
First	First Discharge	92.5 3.3.3 3.3.3 3.3.3	3.88 88 88	2.07
Preconditioning	At 40°C*	,		2.63 (779) 1.31 (328) 2.07 (424) 1.66 (495)
Precon	Initial	3.62 3.27 3.33 3.50	4.00 3.32 4.29 4.29	1.52 1.60 1.55 1.55
Orbit	(Hours)	1.5	1,5 3 3	1,5 3,5
Percent	Depth of	15 15 25 25	25 40 40 40	15 15 25 25
Ambient	Temp.	0000	25 25 25 25	50/40 50/40 50/40 50/40

\* Number in parenthesis indicates number of cycles completed at 50° C.

SONOTONE 5.0 ah PACKS
AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS TABLE IVC

	Third 88 Days First Second	Discharge Discharge					
Capacity Checks	Second 88 Days First Second I	Discharge Discharge Dis		•			
- 00	First 88 Days Last Second	Discharge Di	5.54	3.96 3.96	3.67 4.58	4,38 4,50	2,25
	First	Discharge	3.67 5.75	3.63	3.25	3.04 3.04	1,92
•	Freconditioning At	Initial 40°C*	.45	5.04 4.92	.42	6,42 5,83	3.08 3.63 (703) 3.33 4.92 (223) 3.17 3.17 (445) 3.75 3.50 (183)
	Orbit E	(Hours)		3 4		3 5	1.5 1.5 3.3 3.3
í	Percent Depth of	Discharge	15	25	25 25	0† 0†	15 25 25
•	Amblent Temp.	ပ္စ	00	00	25 25	25 25	50/40 50/40 50/40 50/40

\* Number in parenthesis indicates number of cycles completed at 50° C.

TABLE IVA

GULTON 6,0 ah PACKS

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS

	Third 88 Days	Second	Discharge										
	Third	First	Discharge										
Capacity Checks	Second 88 Days		Discharge				•						
Capacit	Second	First	Discharge										
	First 88 Days	Second	Discharge		5.45		3		3.65				
	First	First	Discharge		4.65	1, %	} •		1,70				
	Preconditioning	At			ı						3.60 (239)	4.55 (239) 2.90 (114)	<b>)</b>
	Precor		Intria	5.00	4.50	5.00 2.25		5.80	5.80 5.40	4.55	2,75	2.75	2.60
;	Orbit	Period	Hours	1,5	ຕູ່	1°2	)	1.5	3.	٣	1,5	3.	i m
i	Percent	Depth of	Ulscnarge	15	15	25 25		25	25 40 50	04	15	15 25	25
•	Ambient	remp.		0	0 (	00		25	25 25	25	20/40	50/±0 50/±0	50/40

\* Number in parenthesis indicates number of cycles completed at 50° C.

TABLE IVe

G.E. 12 ah PACKS

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS

Third 88 Days	First Second Discharge Discharge						
Capacity Checks Second 88 Days	ge q			-			
First 88 Days	Second	13.2	13.0	11.5			
First	First	11.7	11.8	11.7			
Preconditioning	Initial 40°C*	13.9 14.2 4.2	14.6	15.2 15.2 14.8	14.9	6.80 8.20 (334) 7.10 8.20 (205)	
Orbit	Period (Hours)	1,5	<del>)</del> m	1,5 1,5	m	133	<b>.</b> .
Percent	Depth of Discharge	15 15 15	25	22.25 5.55 5.50	O†	15	32
Ambient	Temp.	000	0	2 5 2 2 5 5 5	85	50/40	2 <u>3</u>

\* Mumber in parenthesis indicates number of cycles completed at 50° C.

TABLE IVF

GOULD 20 &h PACKS

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS

	Third 88 Days	Second	Discharge										
	Third (	First	Discharge										
Capacity Checks	Second 88 Days	Second	Discharge				•				*		
Capacit	Second	First	Discharge				,						
	First 88 Days	Second	Discharge										
	First	First	Discharge										
	itioning	At	*0.07		,						6.83 (183)	(1+) 10*	
	Precondition		Initial	22, 5	23.0	23.0	k3.0	25.0	23.3	8* <sub>12</sub>	67		9.33
	Orbit	Period	(Hours)	1.5	m	1,5	m	1.5	ຕຸ	L. U.	1.5	1.5	m
	Percent	Depth of	Discharge	75	15	25	<b>5</b> 2	25	22.	<u></u> 2	15	25	25
	Ambient	Temp.	ပ	O	0	0	0	25	25	2,5 2,5	50/40	5 5 5 5	20.

\* Number in parenthesis indicates number of cycles completed at 50° C.

AMPERE-HOUR CAPACITIES ON PRECONDITIONING CYCLES AND CAPACITY CHECKS TABLE IVE GULTON 20 ah PACKS

Second	Discharge					
First	Discharge					
Second	Discharge		•			
First	Discharge			158.		
Second	Discharge			d on cycle 3		
First	Discharge			Pack faile		
At	3	,			13.8 (172) 12.7 (71)	11.3 (65)
	Initia	17.2 16.7 17.7 21.7	23.3	20.3 23.3 19.8	10.3	9.00
Period	Hours)	1,5	1,5	n.5	1.5	3.5
Depth of	Discharge	15 15 25 25	25	223	15	25 25
Temp.		0000	2.0	2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	20/ <del>1</del> 0 50/10	50/40 50/40
	Depth of Period At First Second First Second First	Depth of Period At First Second First Second First Second First Discharge	Depth of Period         At         First         Second         First         Second         First         Second         First         Second         First         Initial         40°C*         Discharge         Discharge<	Discharge (Hours) Initial 40°C* Discharge Disc	Depth of Discharge         Period         At         First         Second Discharge         First Discharge         Discharge	Depth of Period         At England         First Second         First Second         Intract Second         First Second         Intract Second </td

\* Number in parenthesis indicates number of cycles completed at 50° C.

TABLE V CYCLES COMPLETED AS OF 31 MARCH 1964 ACCORDING TO TEST CONDITIONS AND CELL TYPE

Gulton 20 ah	1160 1159 551 914 807	481 394 560 358* 450 378
Gould 20 ah	1162 1121 1161 710 925	560 1692 1658 1658 1626
G.E 12 ah	1352 1393 1394 1393 1074 889	696 697 788 449 644
Gulton 6.0 ah	1350 1386 1114 1039 967 678	694 701 702 606 619 417
Sonotone 5.0 ah	1634 1569 1616 1630 1417 1127	702 701 702 600 553
Gould 3.5 ah	1808 1805 1806 1794 1449 946	785 781 800 705 649
G.E.	1808 1819 1806 1817 1454 1440	785 781 800 793 696
Orbit Period (Hours)	รรรรร ว่าว่าว่าว่า	๛๛๛๛๛
Percent Depth of Discharge	1,22,24 2,50,57 2,50,57	25 25 25 25 25 25 25 25 25 25 25 25 25 2
Test Temperature	0 25 25 50/40 50/40	0 0 25 25 50/40 50/40

\* Failed on cycle 358.

TABLE VI DATA ON FAILURES THROUGH 31 MARCH 1964

		-					Γ											_								_	Γ
Cell Type	Depth of Discharge	Orbit Period (Hours)	Test Temperature (°C) At Time of Failure	Manufacturer's Serial Number	Cell Number in Pack (Fig. 13)	Cycles Completed	Weight Loss	Low End-of-Discharge Voltage		Low Charge Voltage	Low Voltage on Short Test	Leak at Terminal	Leak at Seam or Weld	High-Pressure Bulge	Concave Walls on Case	Broken Ceramic or Glass	Loose Terminal	Ceremic Short	Burned Case	Distorted Plates or Connectors	Short Above Separator	Short Through Separator	Weak Weld	Foreign Particle	Corrosion at Terminal	Bad Spot on Plates	Bod Onct on Concretous
G.E. 3.0 ah*	15%	1.5	50°	5-41	2	779	x		X		F			-	Ĭ			_			0,2	02	-	-			۲
Gould 3.5 ah	25%	1.5	50°	122	2	408	x	х			Х	N			_		_						?P			-	-
			40°	157	7	484	X	X				N		х													
			40°	158	8	484	X	X	Х			N		X	_												L
			40°	141	5	860	Х	X	X			N		Ц	4											L	L
	25%	3	50°	125	6	138	<u> </u>	X	$\sqcup$		X				4								P		N	_	L
	40%	7 -	50° 25°	65 81	3	495	X	X	-			N			-	X							_				L
	4070	1.5	25	01	7	1609	X	X			X	N		Х										Х			:
Gulton 6.0 ah	15%	1.5	50°	1764	3	239	Х	Х		Х	х							Х									Ī
	25%	1.5	50°	1454	8	37	Π	Х		X	X X							Х									
			50°	1815	6	114	х	X X	Ш	Х		Ш						X									
		<b>!</b>	40°	1853	9	187	х	X	Ш		X	P						X									L
			40°	1627	3	225	х	x	x						_	_											L
	25%	3	50° 40°	2309	8	96	┖	X	Ш		X				_	_	_	X	_	_				_			L
				2346	7	383	L	X	-	Х			X		_			X						_	_		L
	<u> </u>		40°	2306	9	417	┖		X		X			$\sqcup$	_	_	_	Х						_			L
	25%	1.5	25°	2305	1	308	Х	Χ	Х	ļ	_	P		Х	4	_					Ц			_	$\dashv$		L
	100	<u> </u>	25°	2355	10	502	X.	X	X X	ļ		-		X	-	$\dashv$	$\dashv$	_		_	Щ	_		_			Ļ
	40%	1.5	25° 25°	1623 1635	4	2 <b>62</b>	X	Λ	^	x	-	P		X X	Ţ	Ţ			$\dashv$		Н	_		-	$\dashv$		┞
			25°	2356	5		Ŷ	X	v	^	-	F		X	4	^	P	_	$\dashv$				$\dashv$	$\dashv$	-		F
	40%	-	25°	1826	6	450 365	X	Y	1		x	$\vdash$		_	х	-	$\dashv$	X		_	-1	_	-				┝
	15%	1.5	0°	1622	2	1	┢	X	$\vdash$	x		-		H	$\hat{x}$	-		^	х	x	х			-	$\dashv$		⊦
	مرر ـ	1.7	0°	1845	8	6	х			-	-		х						-	-	-						r
Gould 20 ah	40%	3	25°	73	5	222	T		H	х	х			$\mid \mid$	+						Н	х				_	r
Gulton 20 ah	40%	1.5	25°	468	-	163			х					X													
	<u> </u>	<u> </u>	25°	388		208		Х		<u> </u>	X	<b> </b>			4	_	_	P					_	_			L
	40%	3	25°	422	2	153	-	X			<u> </u>	P	_	X	4	_	_		Ц		Щ			_			L
			25°	404	1	153		X			<u> </u>	P		X	_	_	_		Щ			_		_			L
			25°	466	3_	358	Įχ.	+	Х		_	$\vdash$	_	х	_	_	_			_	Ц	_	Щ	_			L
	<u> </u>	<b> </b>	25°	429	5	358	⊢	X	Ш	X	_	Щ			_	_	_	P				_					L
	15%	3	O°	449	2	135	Į.		Ιl	X					Х		- 1		X	Х	X						1

<sup>\*</sup> No post-mortem analysis made to date.

P Positive terminal. N Negative terminal. ? Not definite.

TABLE VII CELL FAILURES ACCORDING TO TEST CONDITIONS AND CELL TYPE AS OF 31 MARCH 1964

Percent Depth of Discharge	य। -	3.5 ah	Sonotone 5.0 ah	Gulton 6.0 ah	G. E.	Gould 20 sh	Gulton 20 ah	TOTALS
	00	00	00	N O	00	00	01	27
3. 3. 3. 3. 3. 3. 3. 3. 3. 3. 3. 3. 3. 3		00	00	00	00	00	00	00
1,5 3 3	0000	0010	0000	80m1	0000	000н	¢000	0000
1.5 1.5 0.00 3.000	0/0	1/13	0000	1/0 0/0 1/2 1/2	0000	0/0	0000	2/0 0/0 2/3 2/3
		7	0	16	0	н	7	32

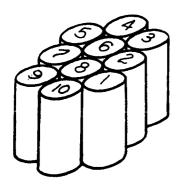
\* Still cycling at 50° C.

# TABLE VIII TYPICAL RANGE OF PACK TEMPERATURE READINGS

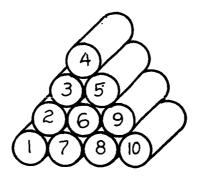
	Ambient	Percent	Orbit	ures							
	Temp.	Depth of	Period	Disch		Char	<b>70</b>				
Cell Type	°C	Discharge	(Hours)	Max.	Min.	Max.	Min.				
G.E. 3.0 ah	0 0 0 25 25 25 25 40 40 50	15 15 25 25 25 25 40 40 15 15 25	1.5 3 1.5 3 1.5 3 1.5 3 1.5 3	4.0 2.8 2.2 3.4 31.4 27.9 36.5 35.0 41.9 42.2 52.3 44.7	0.6 -2.7 -1.3 -1.1 27.8 25.3 28.3 29.5 39.5 40.2 48.3 41.5	4.2 4.0 2.8 31.5 28.3 36.8 34.1 41.9 42.0 52.3 43.7	0.4 -3.1 -1.7 27.5 23.6 28.8 27.9 39.8 38.2 49.5 39.6				
Gould 3.5 ah	0 0 0 25 25 25 25 40 40 40	15 15 25 25 25 25 40 40 15 15 25	1.5 3 1.5 3 1.5 3 1.5 3 1.5 3	4.3 3.5 5.2 4.8 42.1 31.6 41.6 40.0 43.5 42.7 40.4	0.4 -0.7 0.6 -1.1 29.8 27.7 31.5 31.5 40.6 39.5 37.6 42.7	4.2 3.0 4.4 -4.2 41.9 32.0 40.8 42.9 41.6 40.0 44.8	1.1 -2.8 -0.8 -2.8 30.2 26.7 31.2 27.9 40.0 37.9 36.2 40.0				
Sonotone 5.0 ah	0 0 0 25 25 25 25 40 40	15 15 25 25 25 25 40 40 15 25 25	1.5 3 1.5 3 1.5 3 1.5 3 1.5 3	2.0 6.0 3.3 4.0 39.6 34.2 38.1 36.0 45.8 43.9 44.6	-2.3 1.3 -0.7 -2.9 34.5 29.1 27.3 29.6 38.0 41.2 39.3 41.2	3.2 6.0 2.8 1.2 39.1 34.3 38.1 37.0 44.1 45.0 44.8	-1.9 -0.8 -0.3 -3.9 34.1 28.3 32.7 29.3 38.4 40.0 37.9 41.0				
Gulton 6.0 ah	0 0 0 25 25 25 25 40 40	15 15 25 25 25 25 40 40 15 25 25	1.5 3 1.5 3 1.5 3 1.5 3 1.5 3	3.4 4.4 2.8 4.8 31.5 31.9 33.3 45.6 44.8 40.8	-2.9 1.1 -0.3 -0.7 26.5 26.8 28.7 27.3 39.3 40.8 40.9 37.9	3.1 6.0 4.0 31.8 31.4 36.1 36.0 46.0 44.6 45.9	-3.3 -1.5 -1.2 -0.7 27.3 25.0 28.5 26.8 37.6 40.0 41.0 38.0				

# TABLE VIII (Contd)

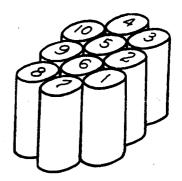
	Ambient	Percent	Orbit	Temperatures				
	Temp.	Depth of	Period	Discharge			Charge.	
Cell Type	<u>°C</u>	Discharge	(Hours)	Max.	Min.	Max.	Min.	
G.E. 12 ah	0	15	1.5	2.8	-2.5	1.4	-2.5	
	0	15	3	3.3	-0.9	3.2	-3.1	
	0	25	1.5	3.2	-3.5	3.1	-0.9	
	0	25	3	4.0	0.2	3.2	-1.1	
	25	25	1.5	30.0	26.0	30.5	27.1	
	25	25	3	32.0	26.0	30.4	23.8	
	25	40	. 1.5	35.4	29.8	36.4	30.2	
	25	40	3	35.0	27.5	35 <b>.</b> 8	25.8	
•	40	15	1.5	41.6	37.5	40.8		
	40	15	3	41.9	38.1	41.0	37.6	
	40	25	1.5	47.3	41.4		38.1	
	40	25		1.1. 0		47.3	40.1	
	70	2)	3	44.8	39.6	42.9	39.2	
Gould 20 ah	0	15	1.5	8.8	1.1	8.2	0.8	
	0	15	3	4.0	-2.7	2.0	-1.3	
	0	25	1.5	9.2	-1.3	8.0	-0.9	
	0	25	3	3.0	-3.9	3.1	-1.1	
	25	25	1.5	28.3	27.2	28.5	27.3	
	25	25	3	30.6	25.8	30.0	23.7	
	25	40	1.5	42.9	37.5	42.7	37.9	
	25	40	3	39.6	31.2	37.0	27.9	
	40	15	1.5	41.6	36.0	42.1	36.8	
	40	15	3	41.6	38.6	42.7	38.1	
	50	25	1.5	51.4	49.1	51.0	49.4	
	50	25	3	55.0	49.6	51.4	49.6	
	•					74.4	49.0	
Gulton 20 ah	0	15	1.5	3.2	-1.9	4.0	-0.7	
	` 0	15	3	3.2	-4.1	1.2	-2.8	
	0	25	1.5	4.8	-0.7	5.4	2.8	
	0	25	3	3.3	-2.8	2.8	-3.3	
	25	25	1.5	30.3	27.3	32.5	26.2	
	25	25	3	31.2	26.0	31.8	27.3	
	25	40	1.5	42.9	38.0	44.2	38.1	
	25	40	3	36.2	25.4	38.0	26.2	
	40	15	1.5	41.9	40.0	42.0	39.6	
	40	15	3	41.9	38.1	42.0	37.7	
	40	25	1.5	42.7	38.8	42.9	38.1	
•	40	25	3	43.5	39.5	45.8	41.4	



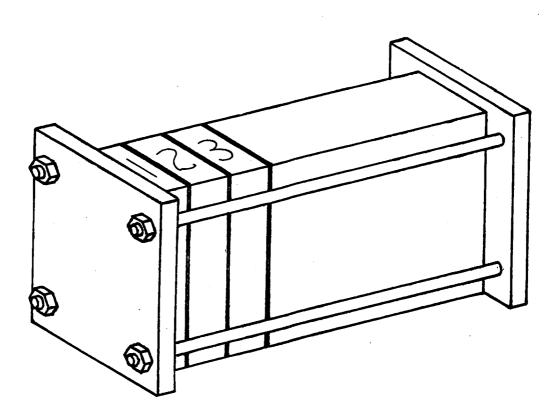




b. Gould 3.5 ah



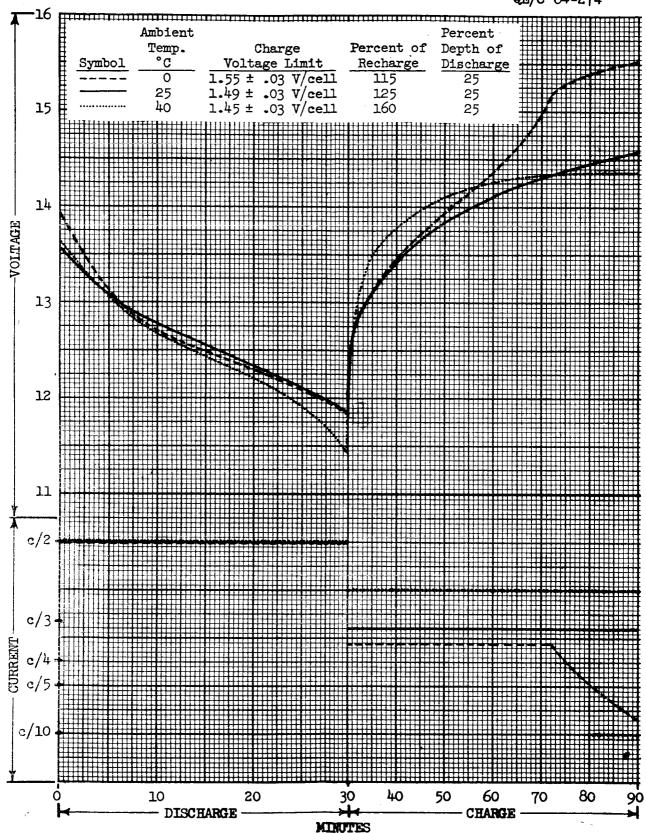
c. Sonotone 5.0 ah



d. All Rectangular Cells

Diagram of Pack Arrangements (Numbers identify cell position and electrical sequence)

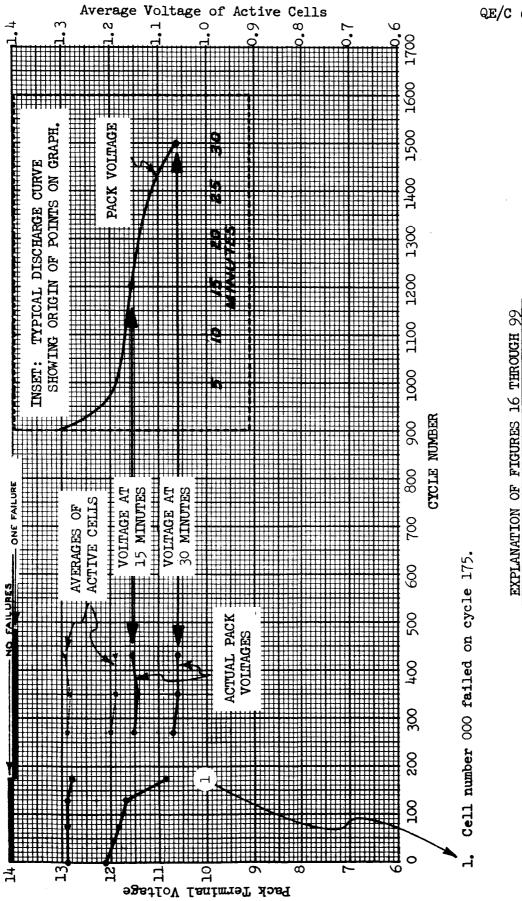
FIGURE 13

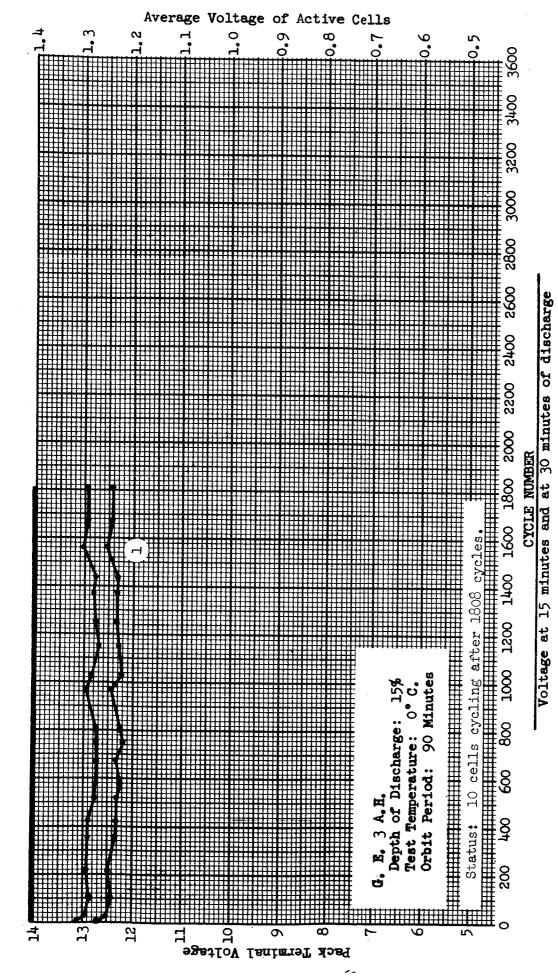


TYPICAL CHARACTERISTIC CURVES ON CHARGE AND DISCHARGE FOR A PARTICULAR ORBIT PERIOD, DEPTH OF DISCHARGE, AND CELL TYPE

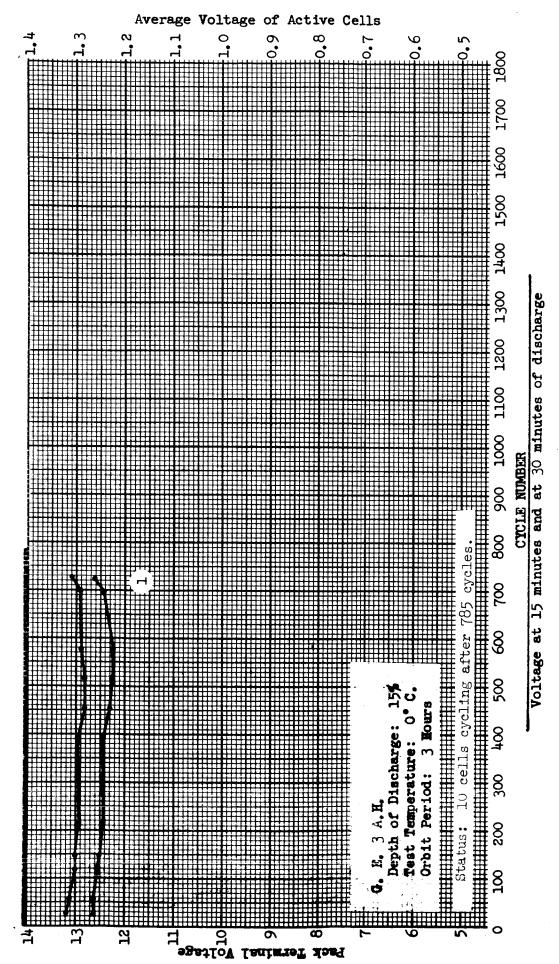
FIGURE 14





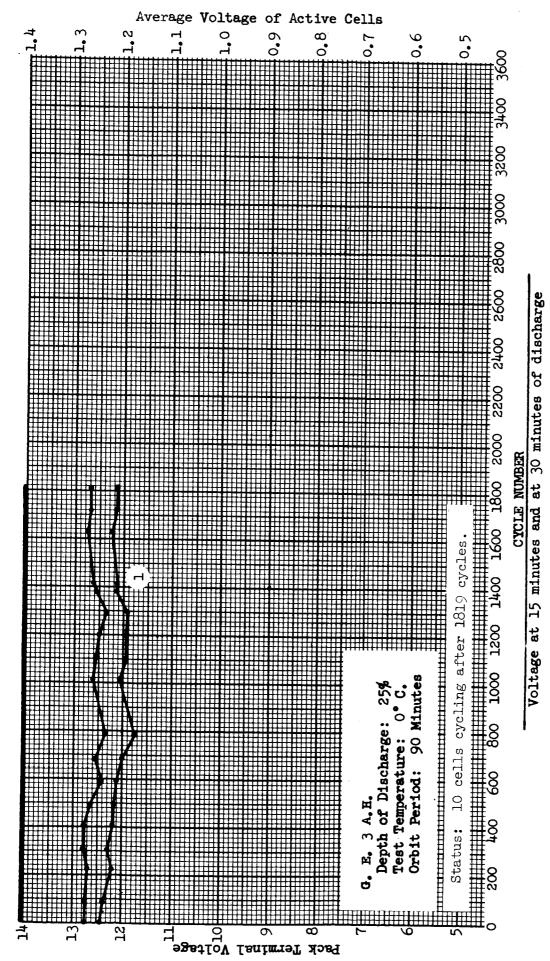


1. Capacity check followed cycle 1546.

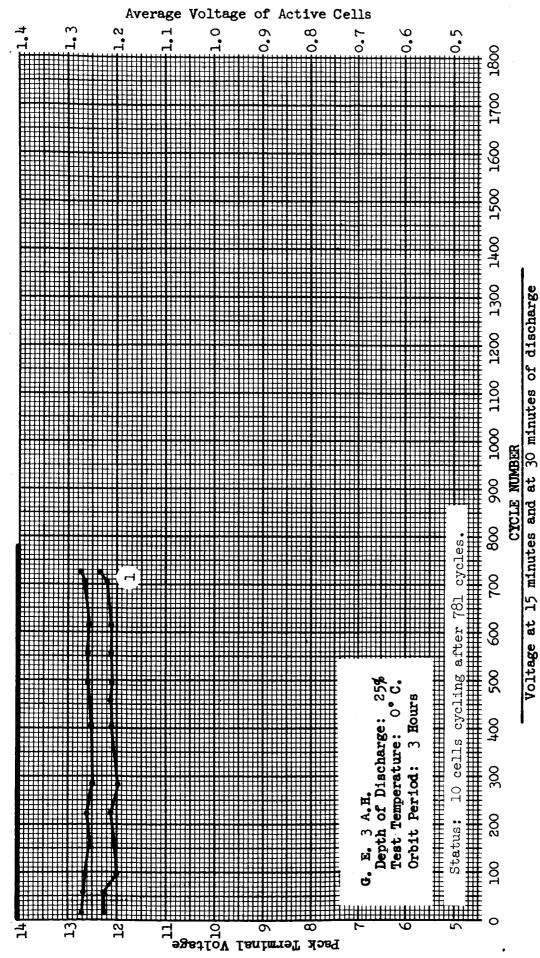


Capacity check followed cycle 719.

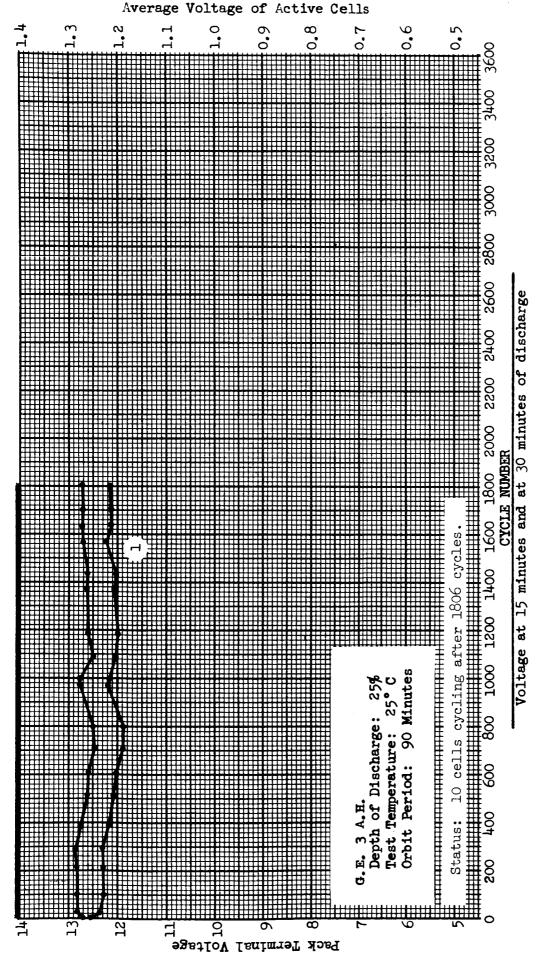




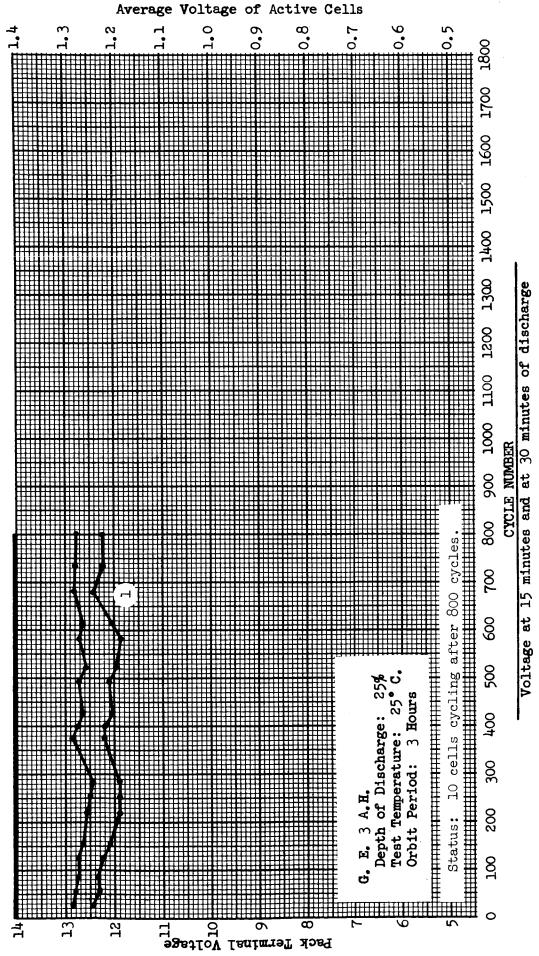
. Capacity check followed cycle 1442,



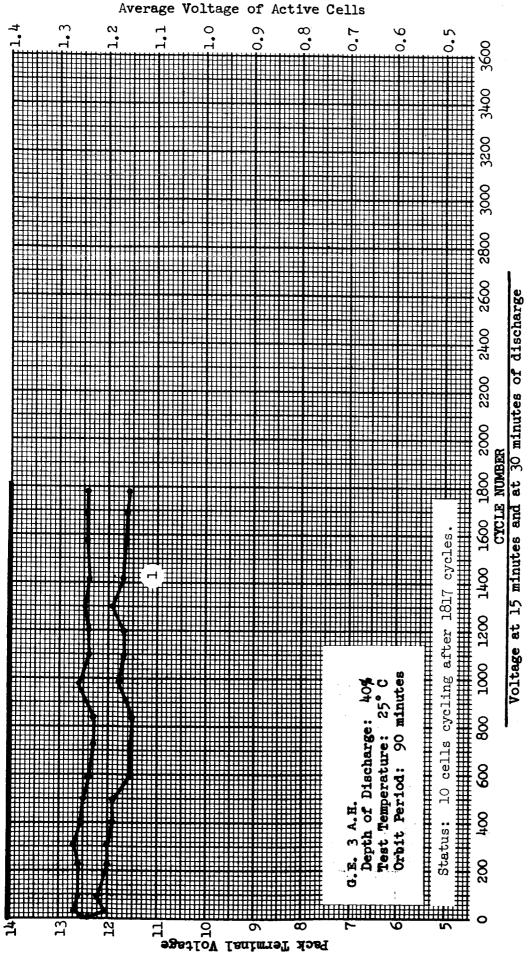
. Capacity check followed cycle 715.



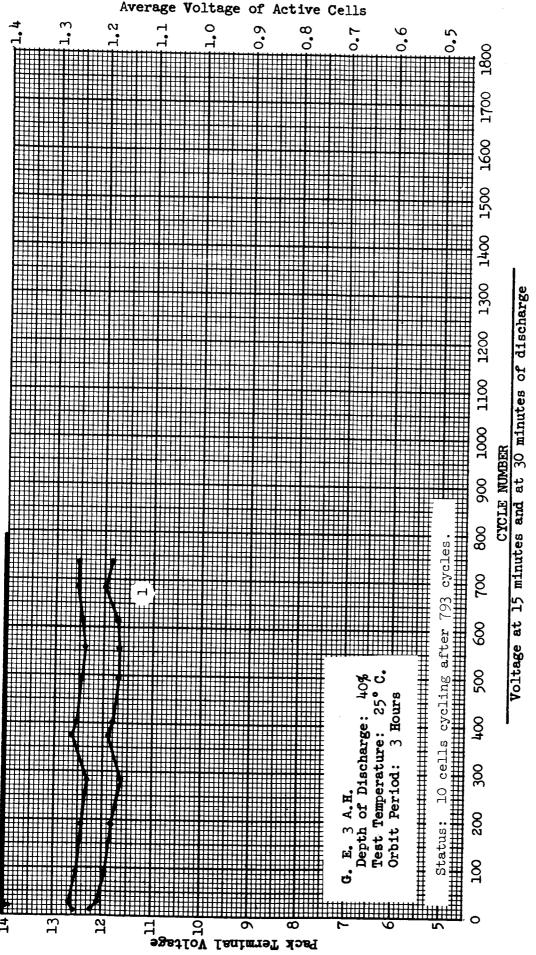
1. Capacity check followed cycle 15444.



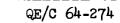
L. Capacity check followed cycle  $67\mu_{\bullet}$ 



1. Capacity check followed cycle 1427.



Capacity check followed cycle 676.



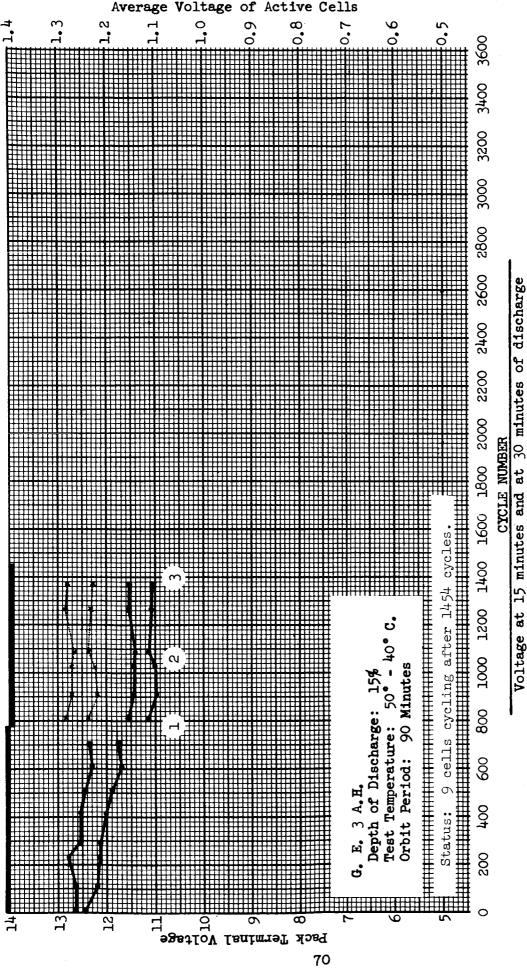


FIGURE 24

Charge voltage limit raised to 1,45 V/cell

8

Capacity check followed cycle 1400.

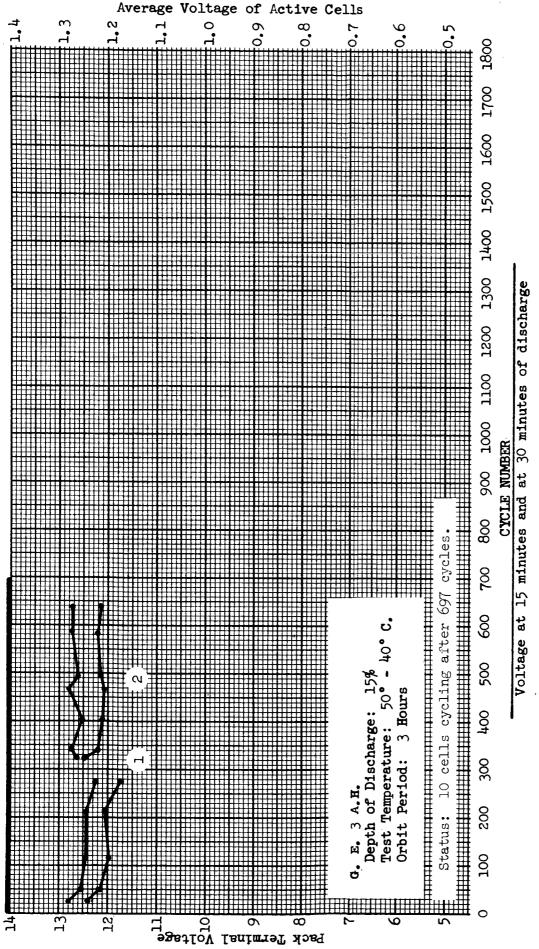
number 541 failed during preconditioning.

Changed to 40° C. after cycle 779.

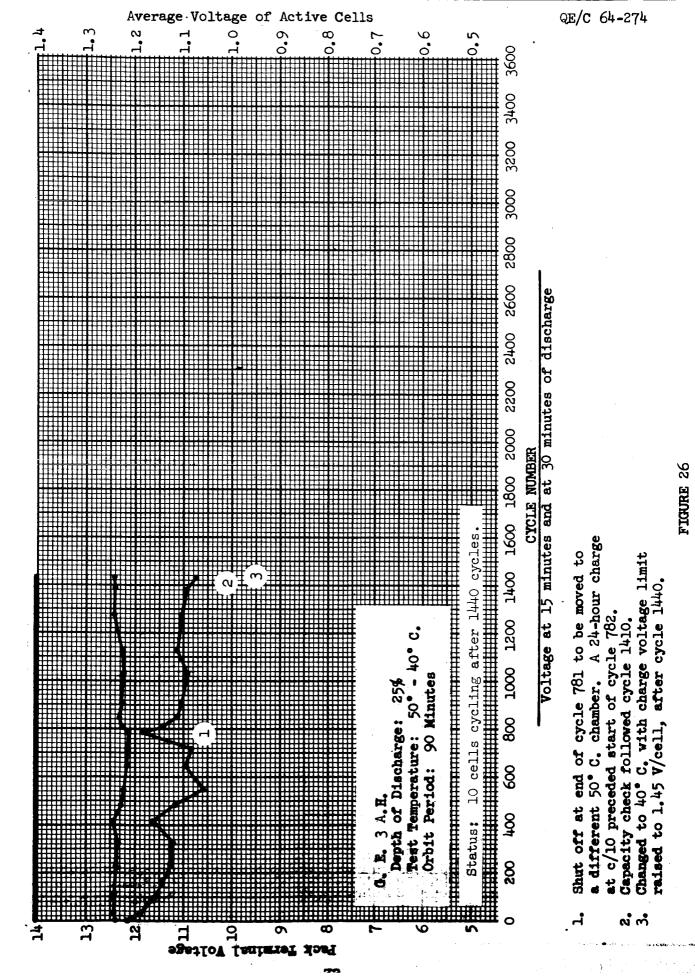
Cell

Changed to 40° C. after cycle 320. Charge voltage limit raised to 1.45 V/cell

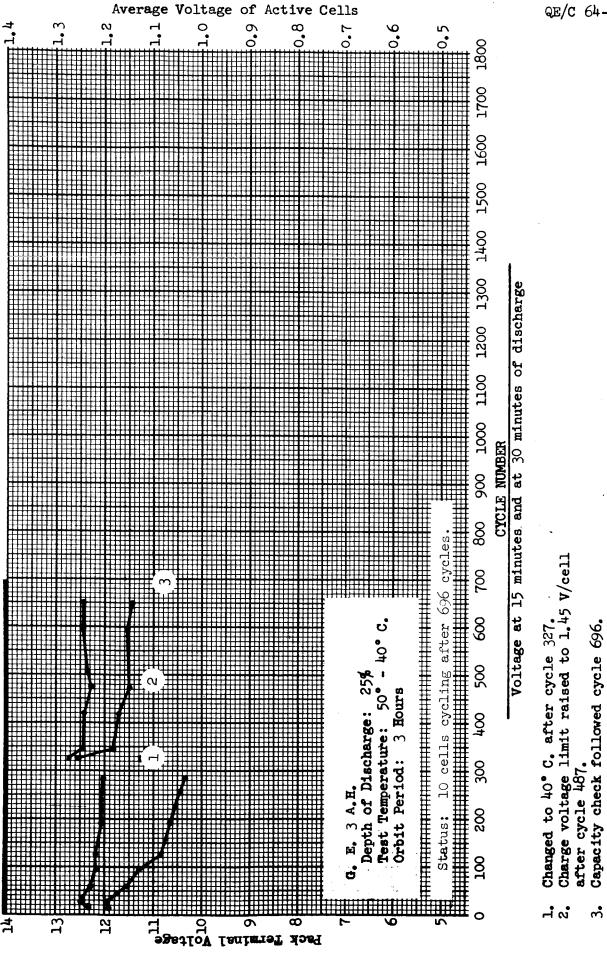
۲. %



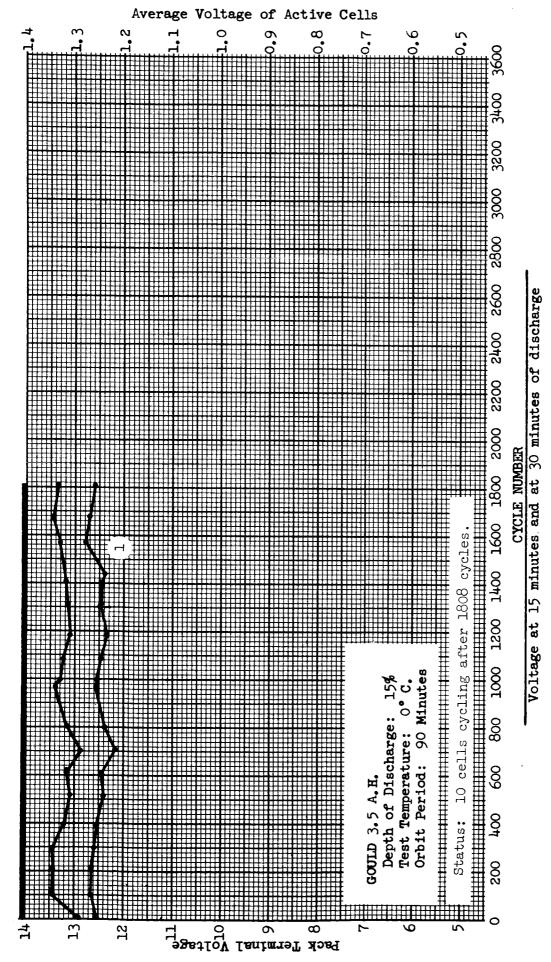
71



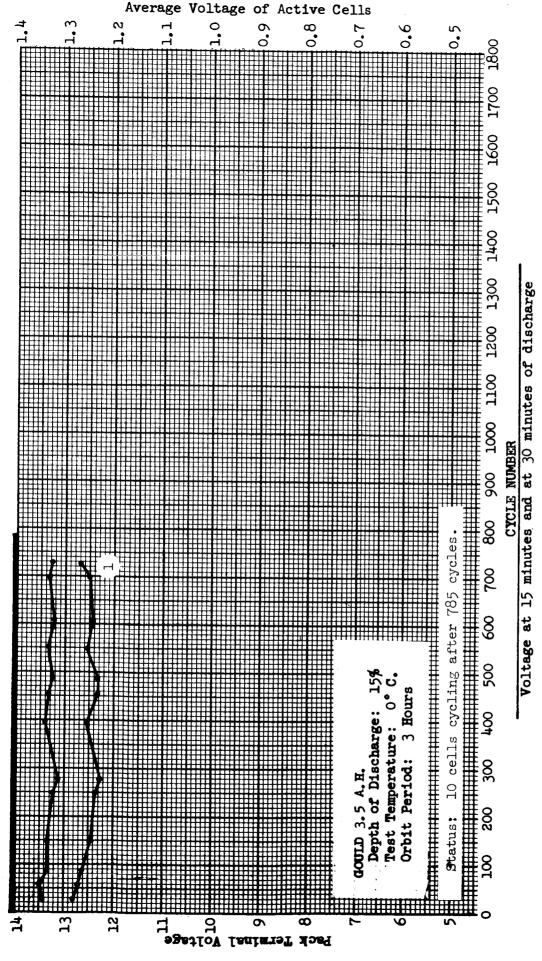




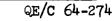
73

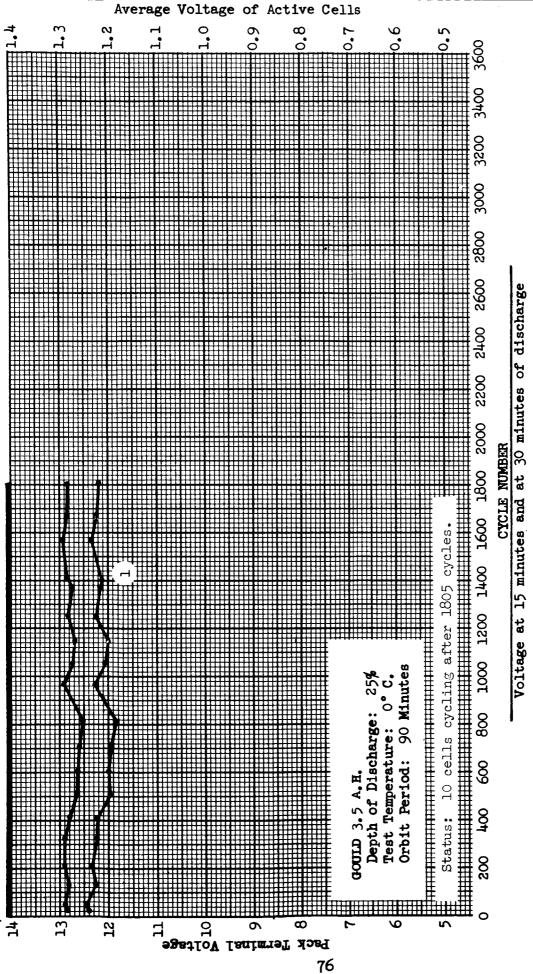


1. Capacity check followed cycle 1546.

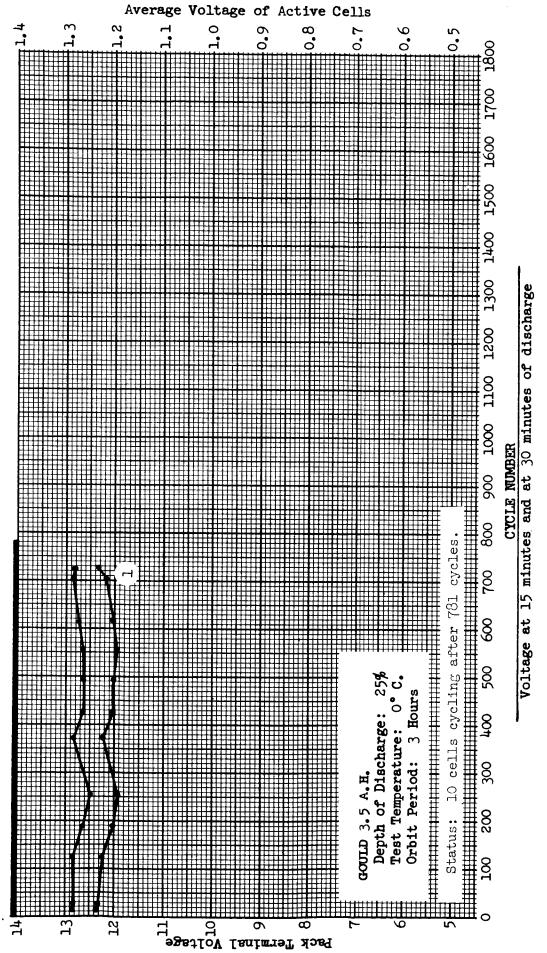


1. Capacity check followed cycle 719.



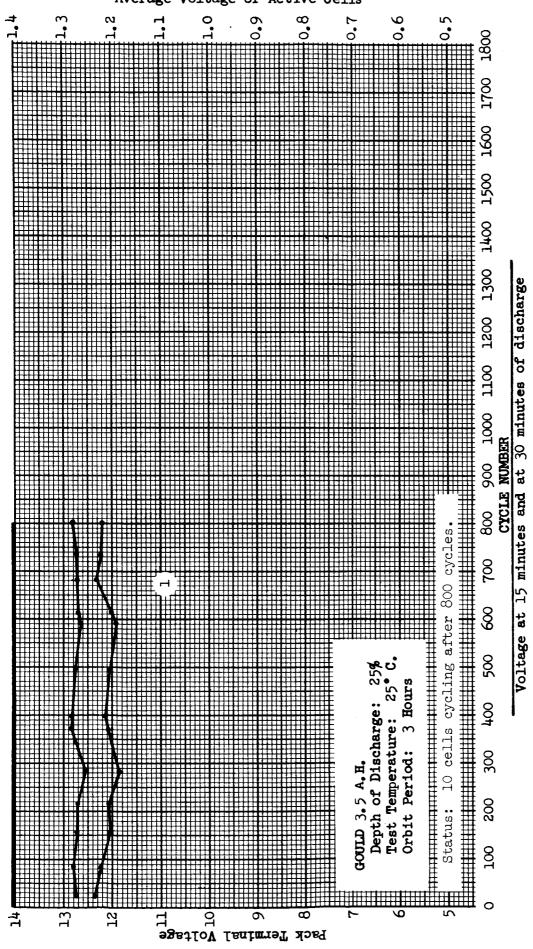


Capacity check followed cycle 1428.

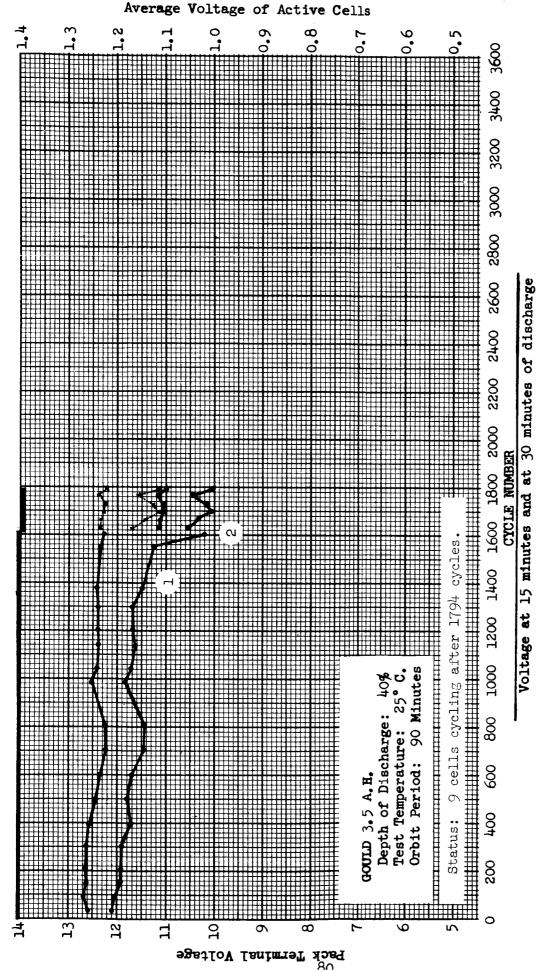


1. Capacity check followed cycle 715.

1. Capacity check followed cycle 1544.



1. Capacity check followed cycle  $67\mu_{\bullet}$ 



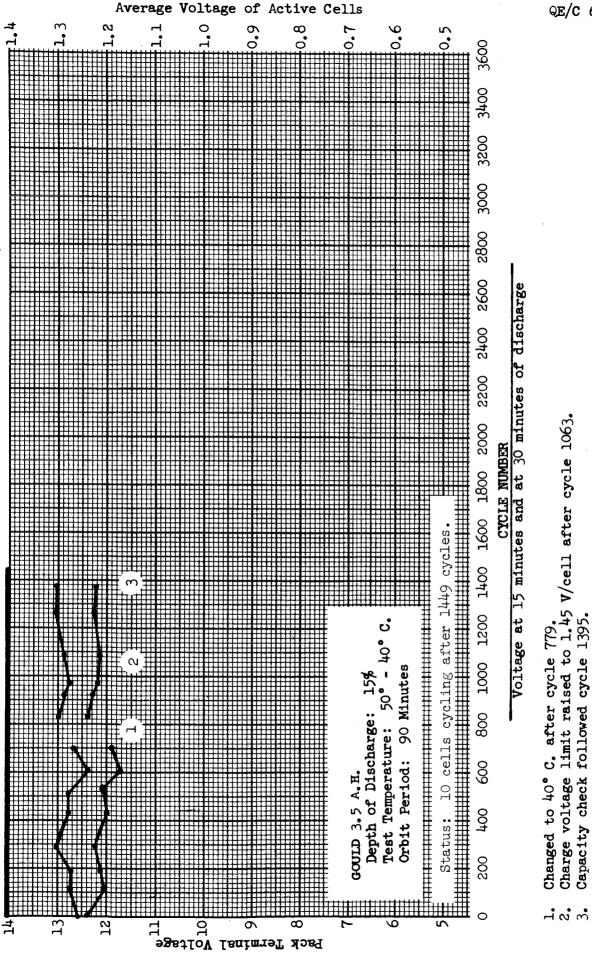
Capacity check followed cycle 1404.
 Cell No. 81 failed on cycle 1609.

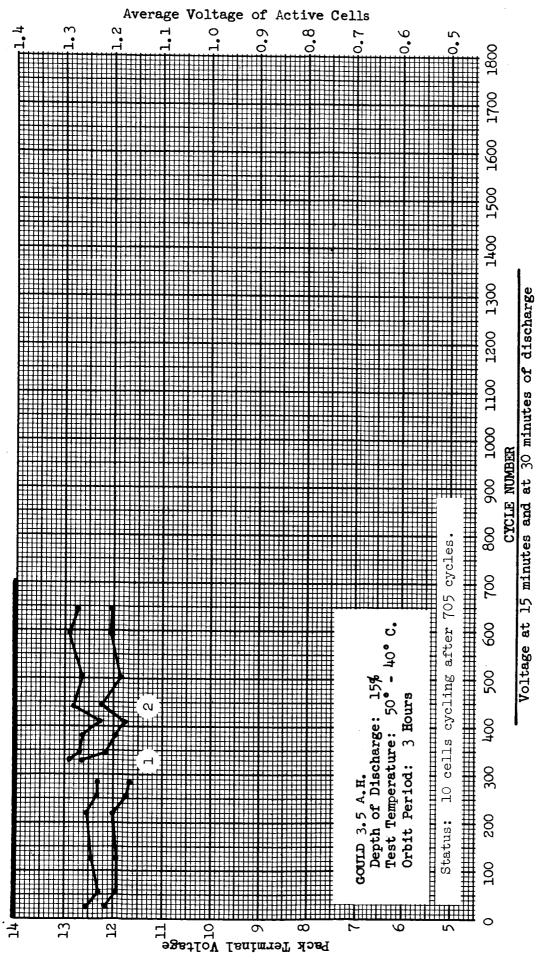


QE/C 64-274

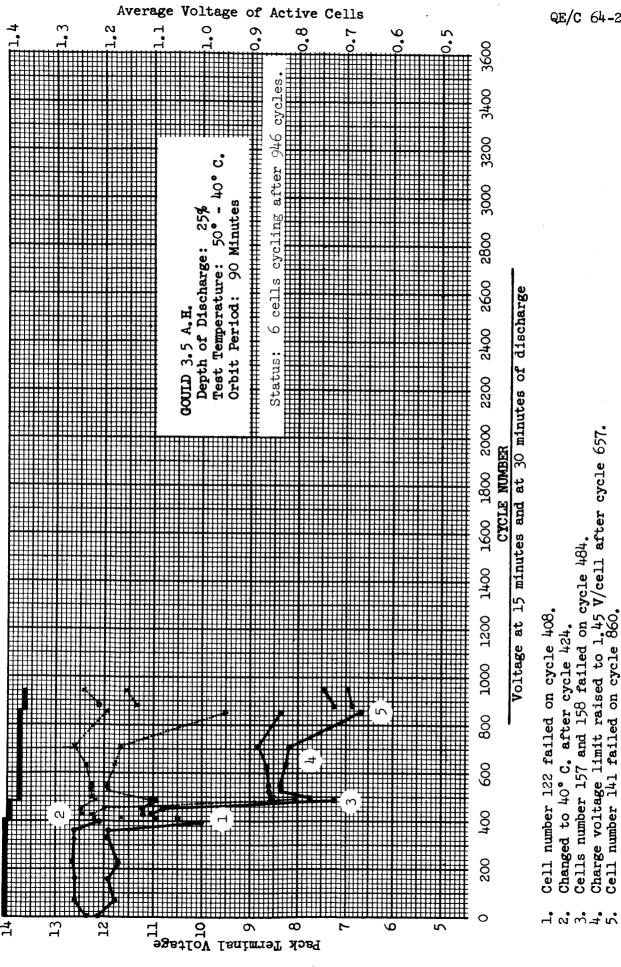
Pack Terminal Voltage

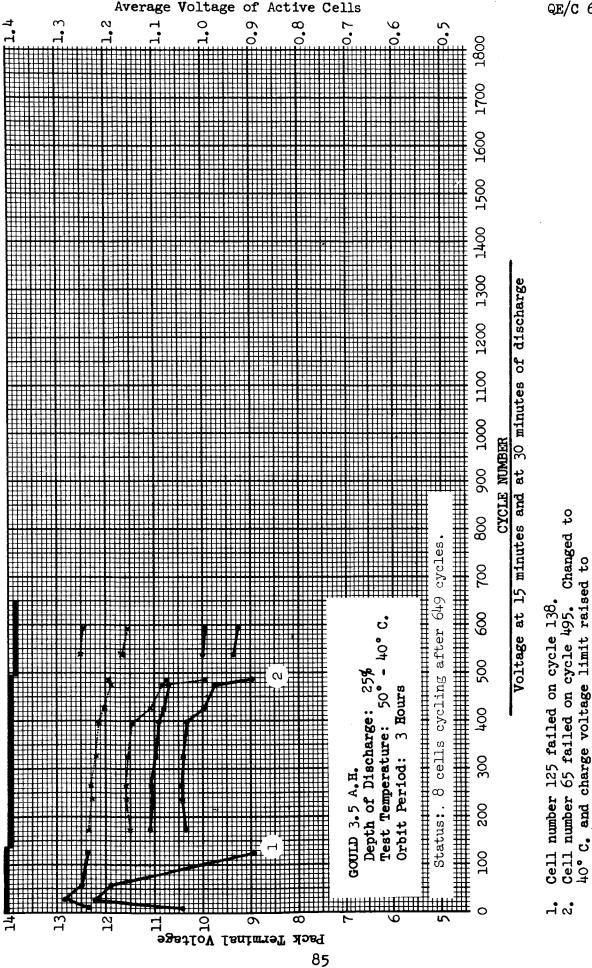
12

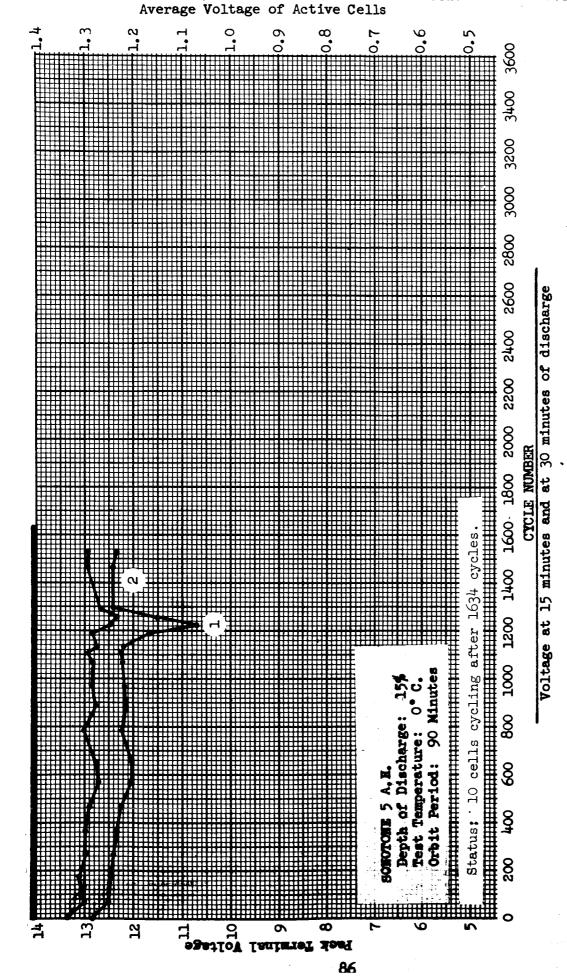




Changed to 40° C. after cycle 328.
 Charge voltage limit raised to 1.45 V/cell after cycle 486.

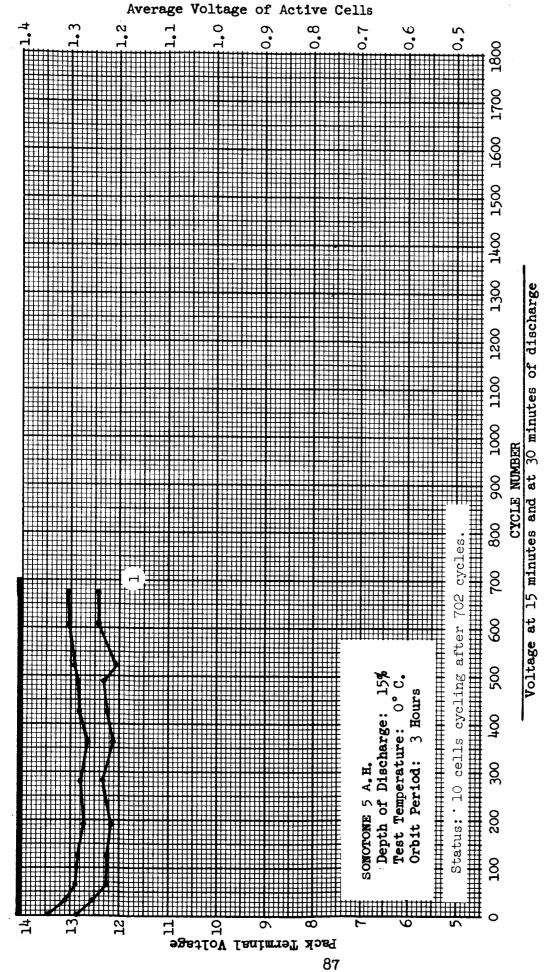




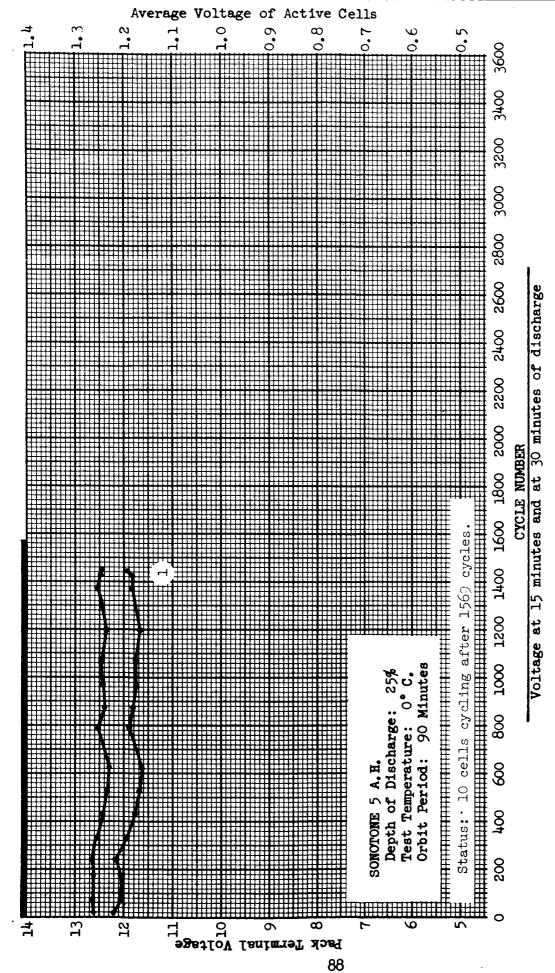


Cell number 6887 appeared to be failing between cycles 1200 and 1250 but became

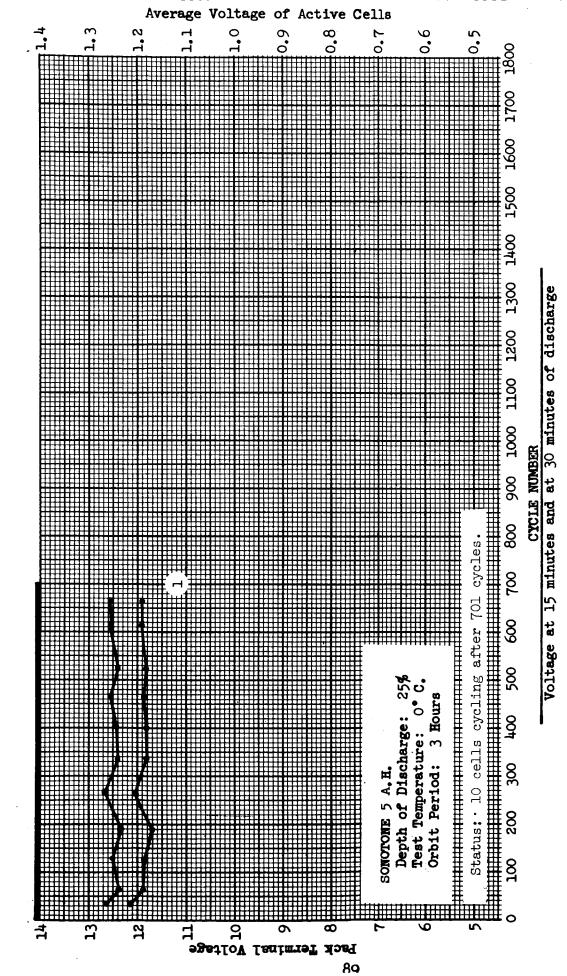
normal by cycle 1300. Gapacity check followed cycle 1405.



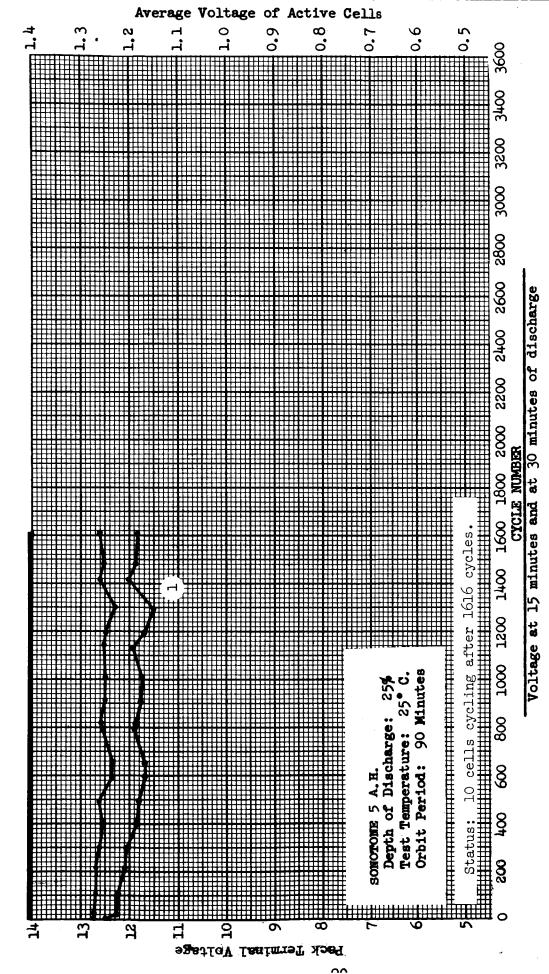
1. Capacity check followed cycle 702.



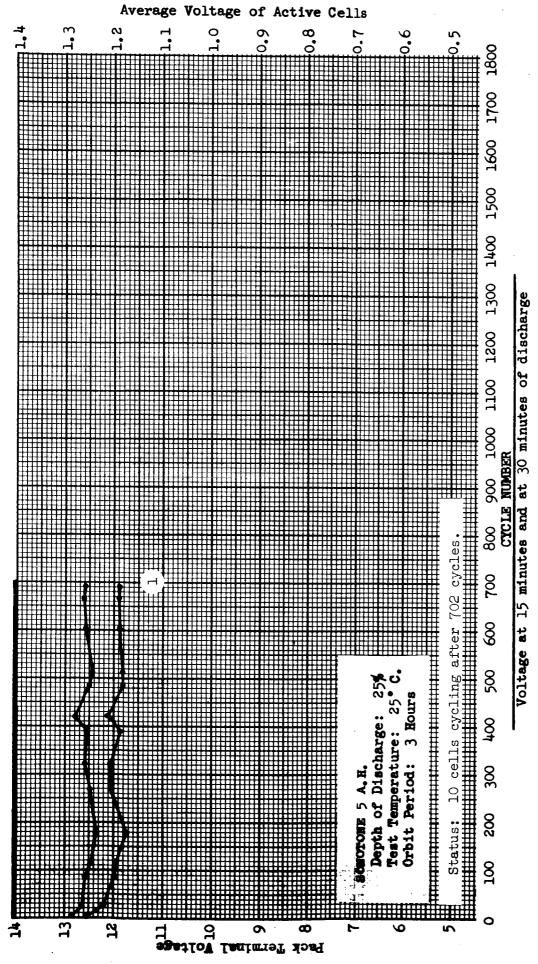
1. Capacity check followed cycle  $1^{4}35$ .



1. Capacity check followed cycle 701.

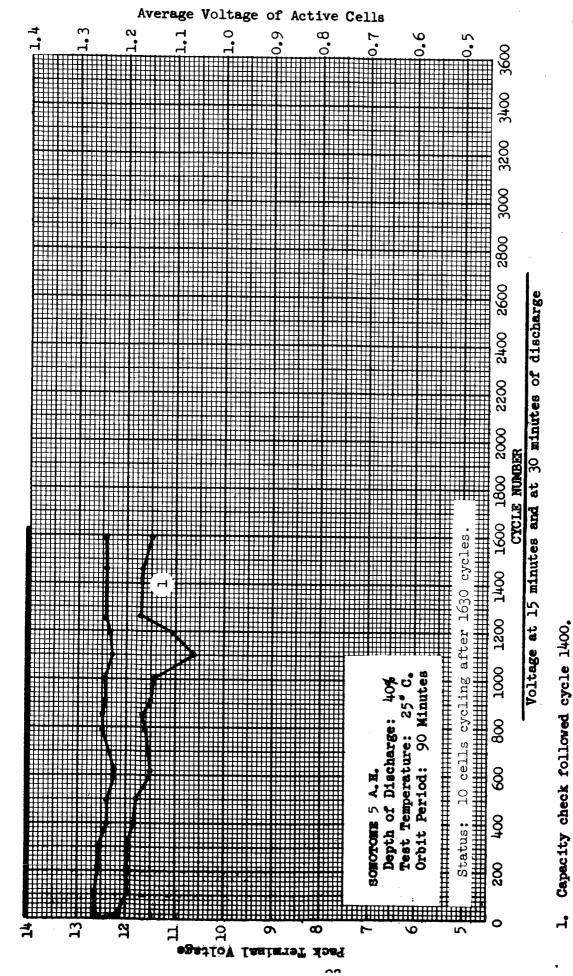


. Capacity check followed cycle 1387.

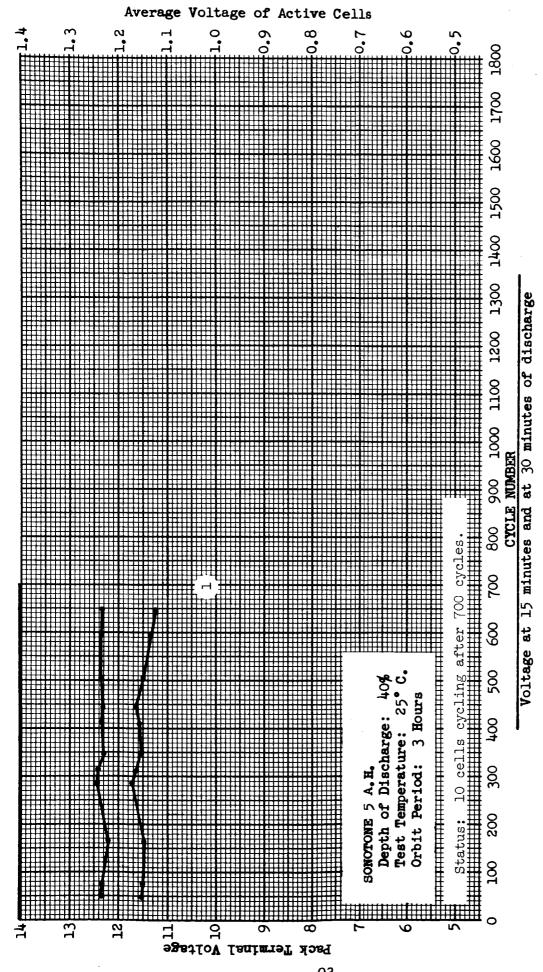


1. Capacity check followed cycle 702.









Capacity check followed cycle 700.

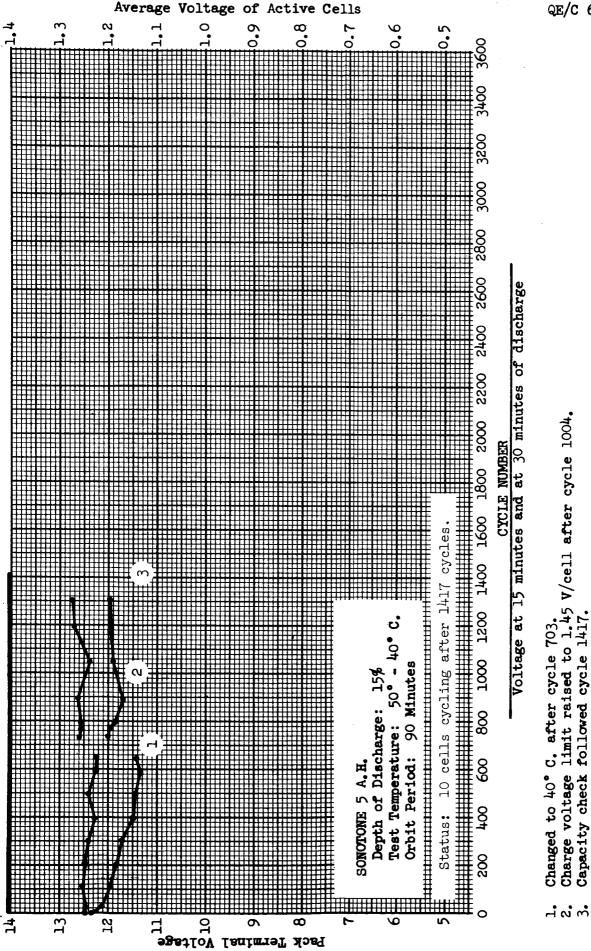
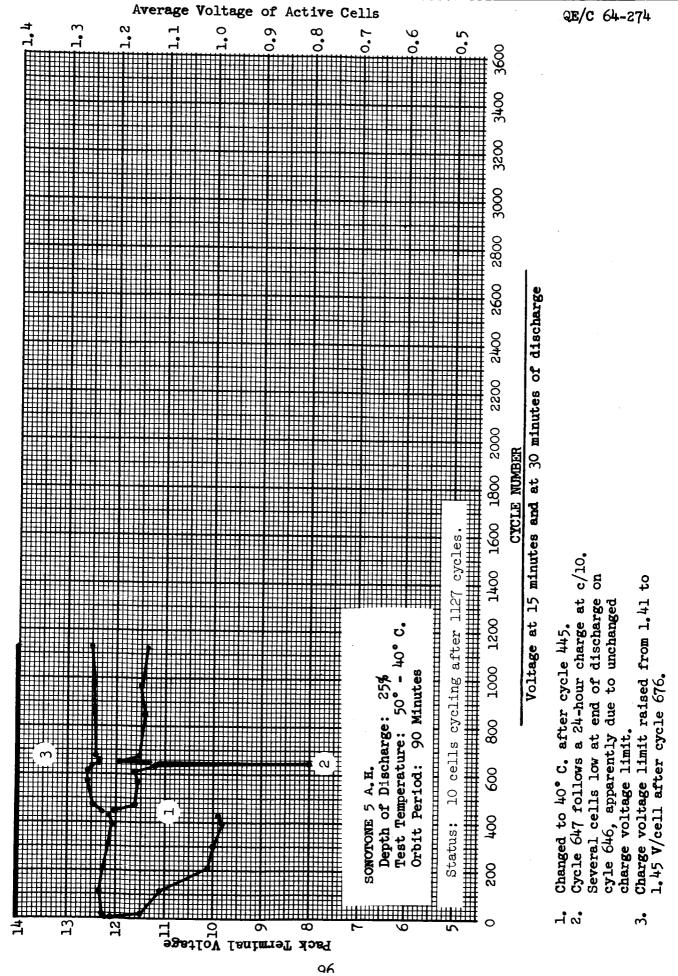
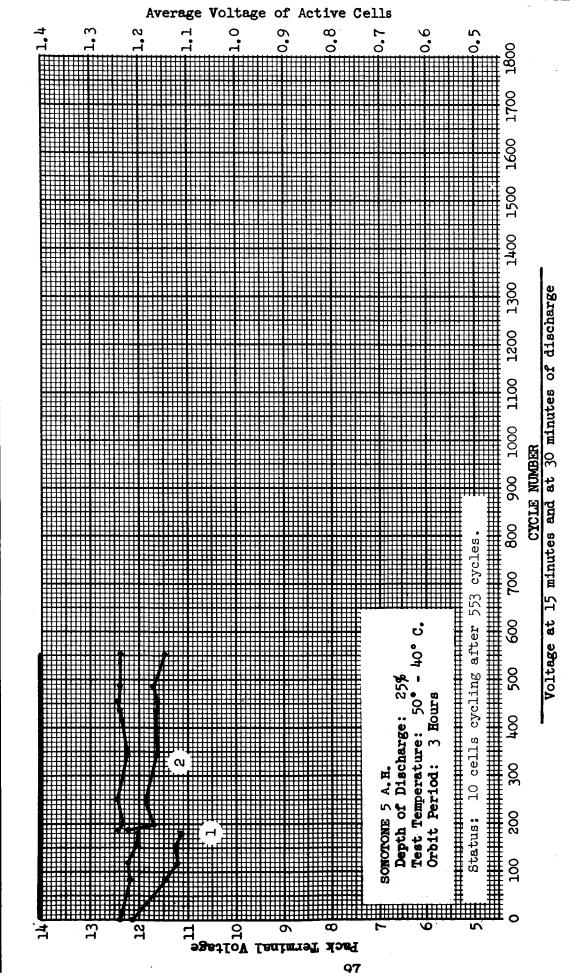


FIGURE 49

Changed to  $40^{\circ}$  C, after cycle 223. Charge voltage limit raised to 1,45 V/cell after cycle 381.

4.9





Changed to 40° C. after cycle 183.
 Charge voltage limit raised to 1.45 V/cell after cycle 329.



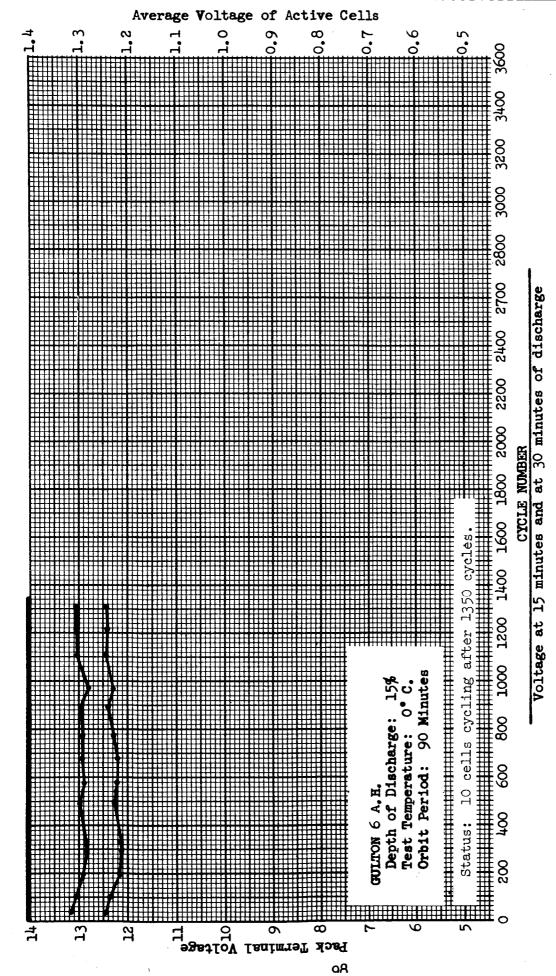
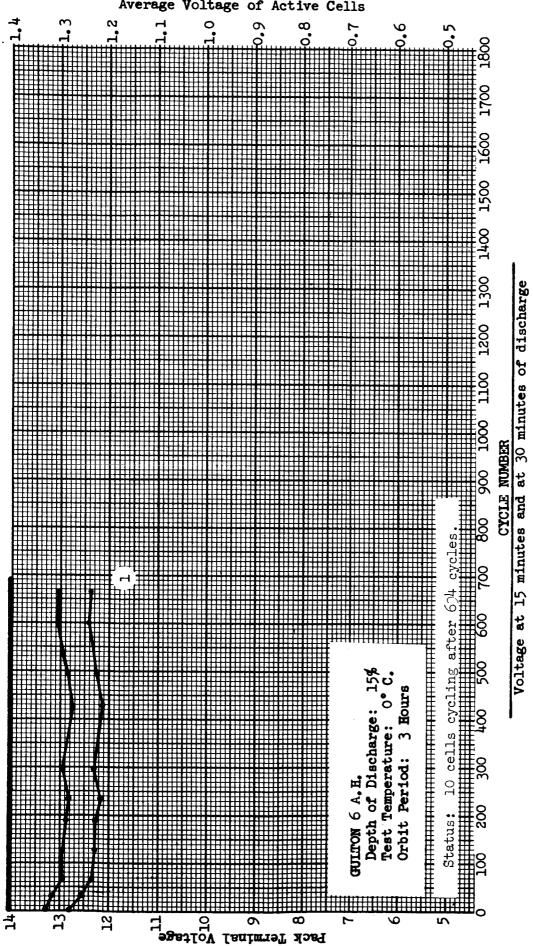
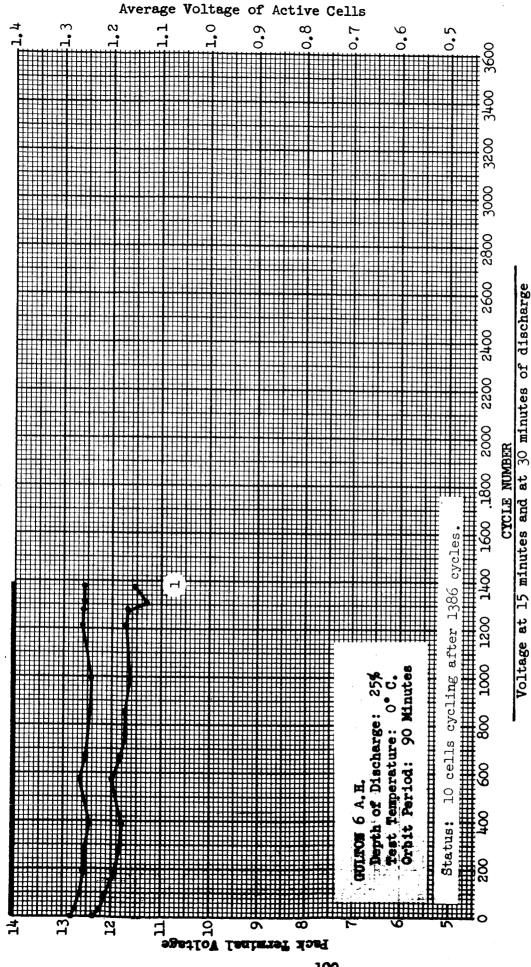


FIGURE 52



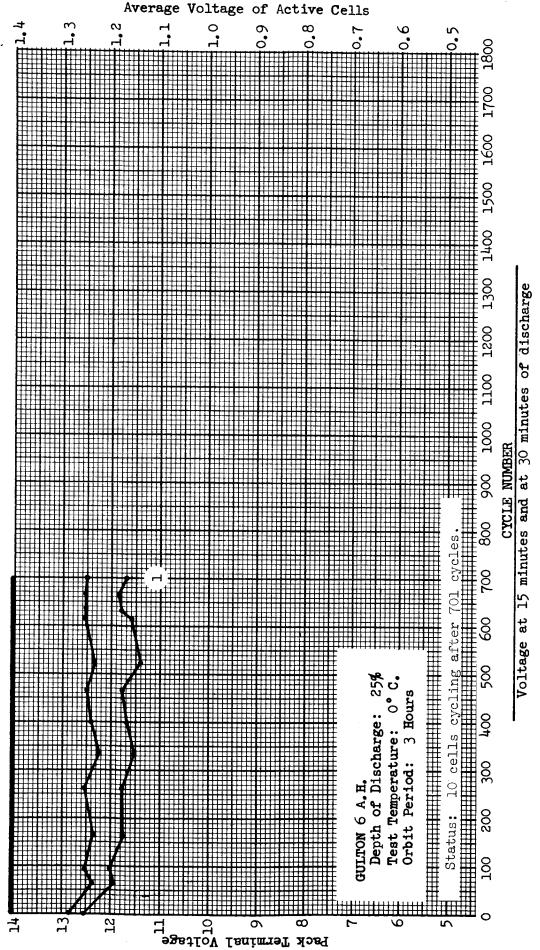


Capacity check followed cycle 694.

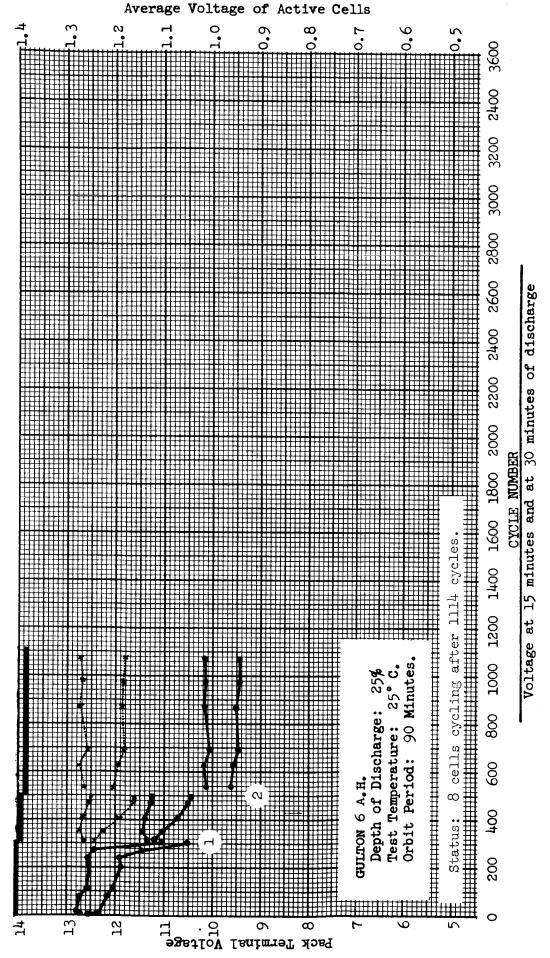


Capacity check followed cycle 1386.

PIGHRE 54

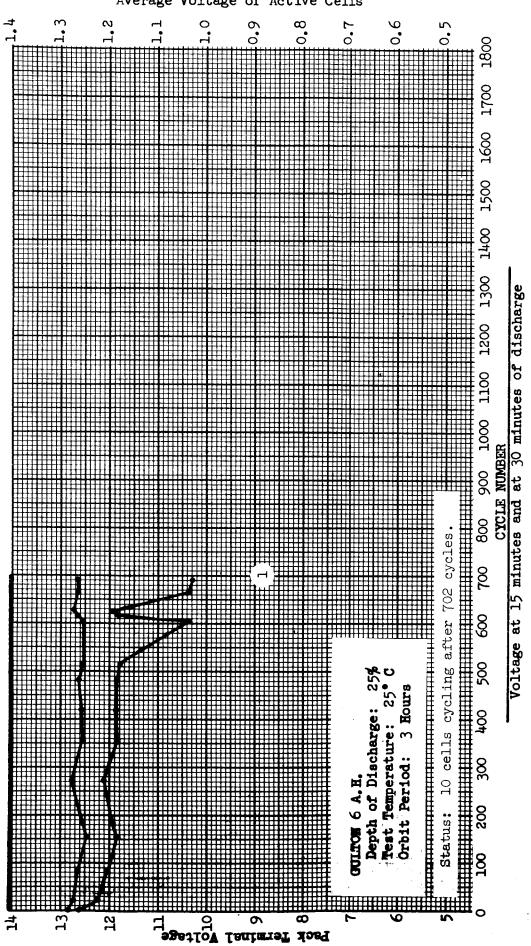


. Capacity check followed cycle 701,



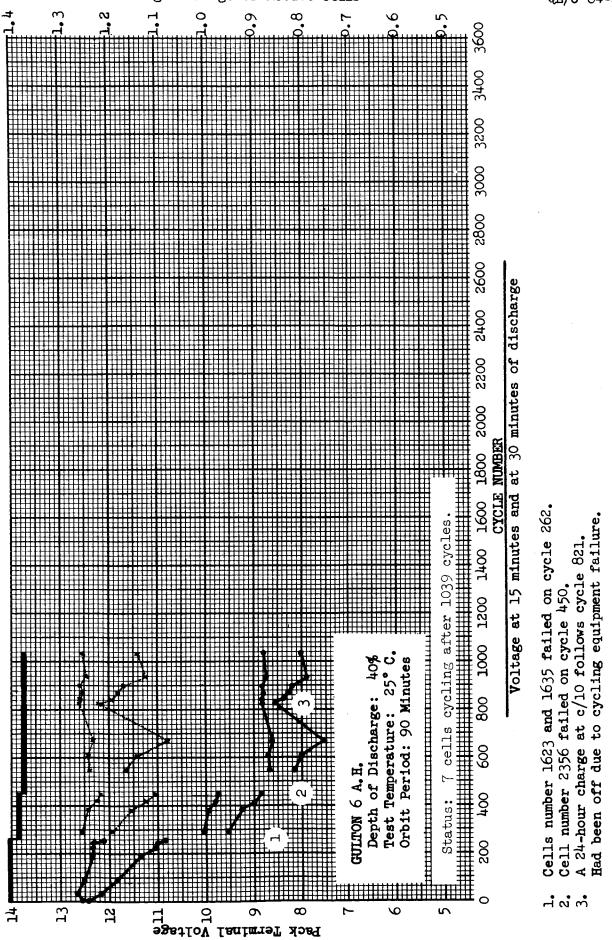
1. Cell number 2305 failed on cycle 308.
2. Cell number 2355 failed on cycle 502.





. Capacity check followed cycle 702.







Cell number 1826 failed on cycle 365. Remainder charged for  $2^4$  hours at c/10 before returning to

A 24-hour charge at c/10 followed cycle 511. Had been off for cycling equipment repair.

cycling.

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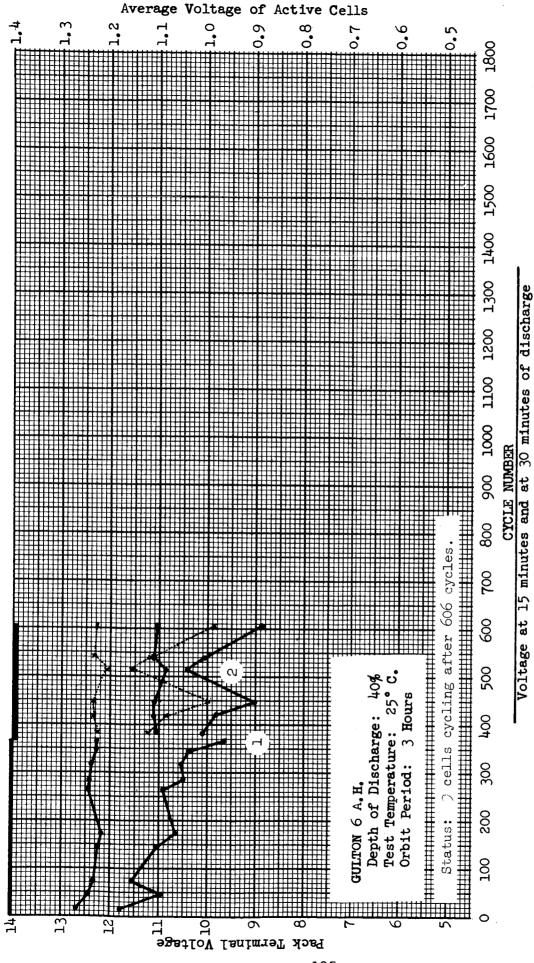


FIGURE 60

Charge voltage limit raised to 1.45 V/cell

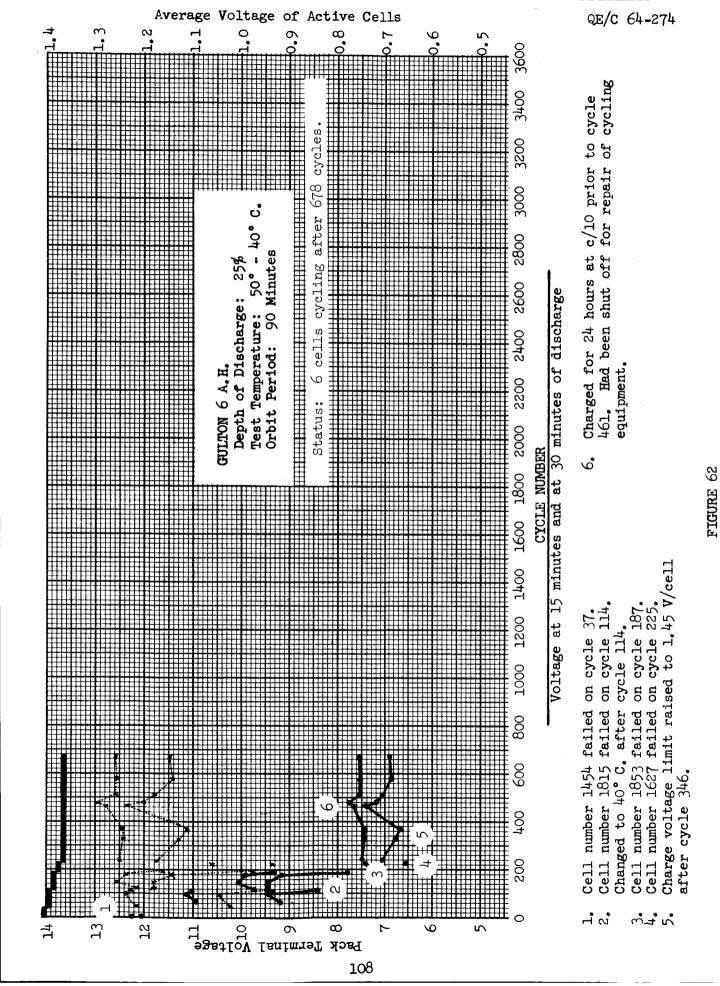
after cycle 527.

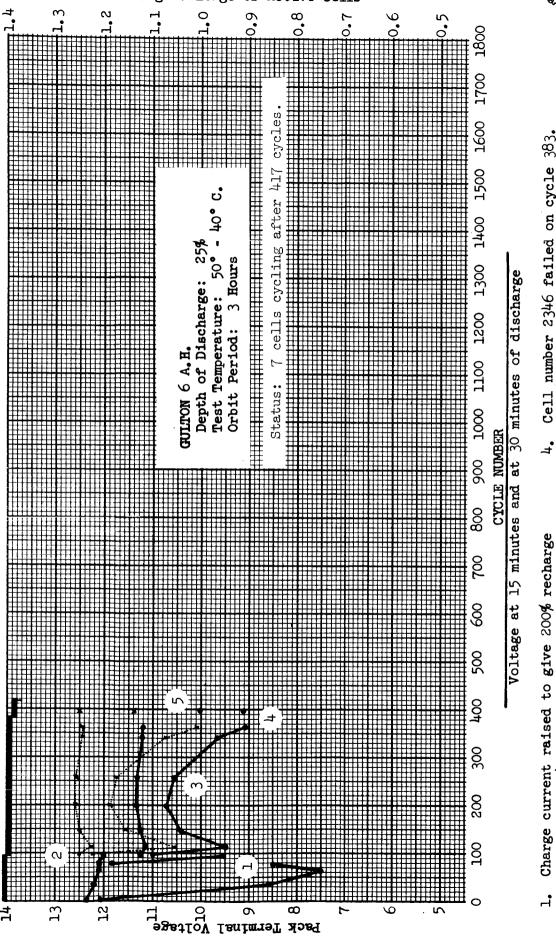
8

Cell number 1764 failed on cycle 239.

Changed to 40° C. after cycle 239

1. Changed to  $40^{\circ}$  C. after cycle 239. 2. Charge voltage limit raised to 1.45 V/cell after cycle 397.





Cell number 2346 failed on cycle 383. Cell number 2306 failed on cycle 417.

after cycle 243,

Cell number 2309 failed on cycle 96. Changed

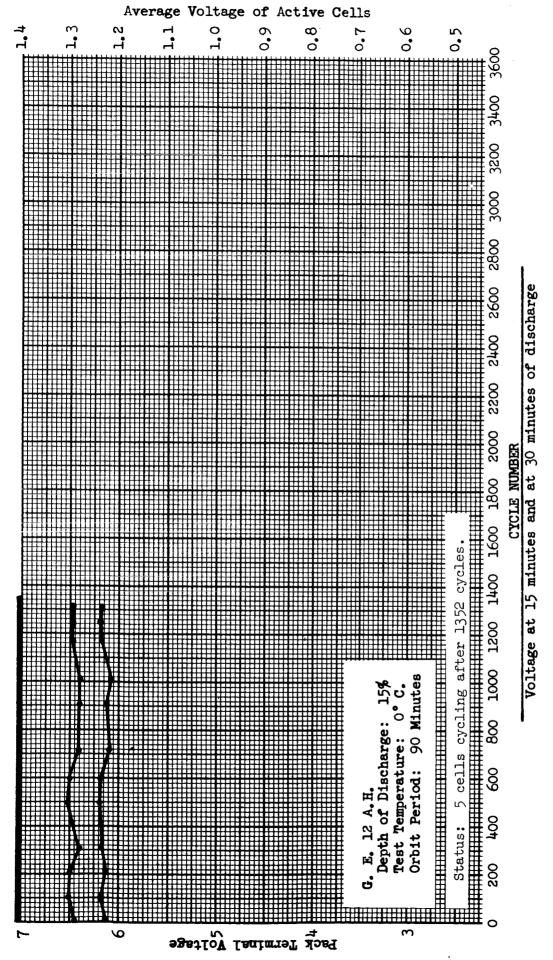
after cycle 74

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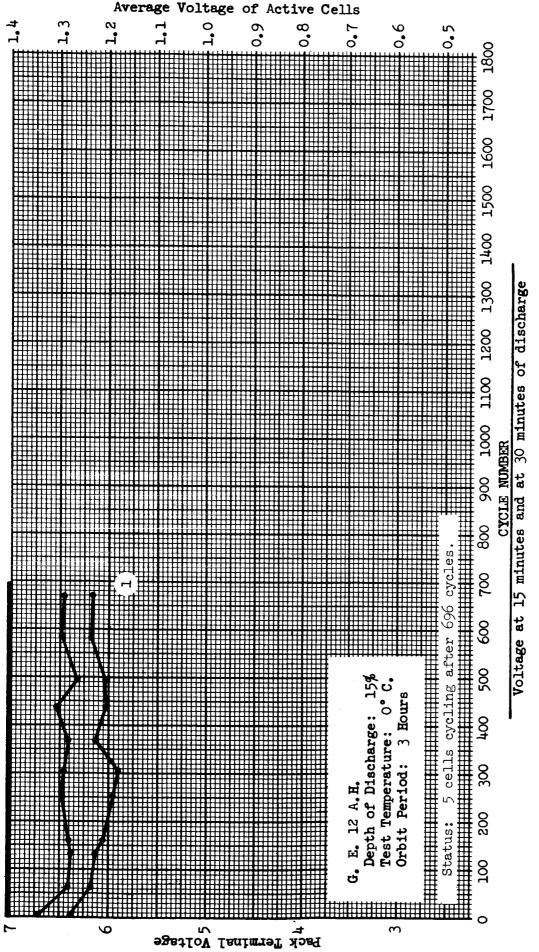
Charge voltage limit raised to 1,45 m V/cell

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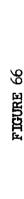
o 40° C., 160% recharge after cycle 96.

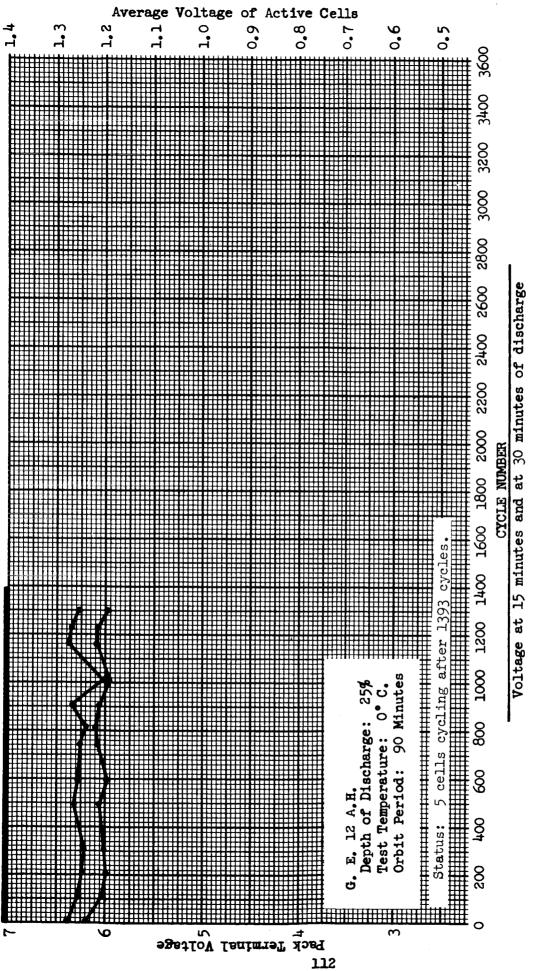






. Capacity check followed cycle 696.



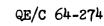


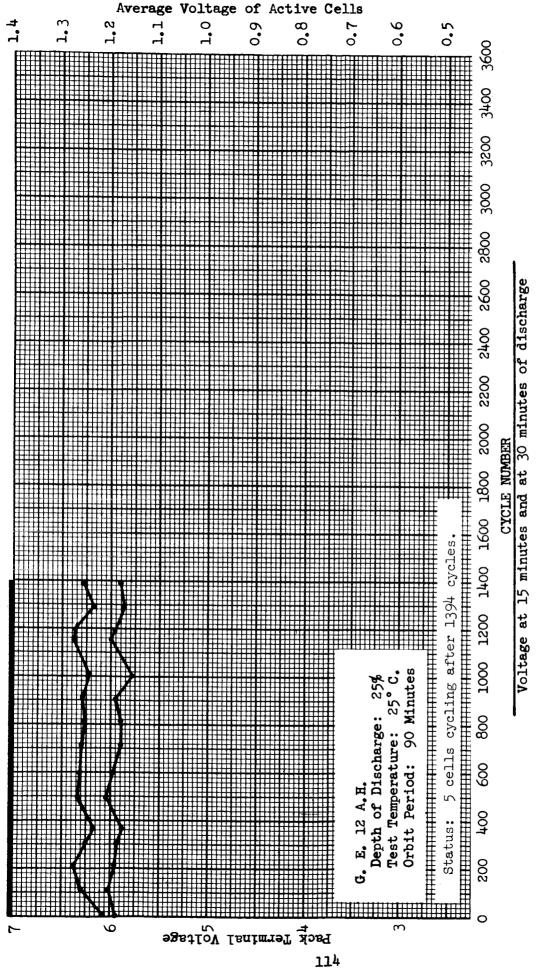
Ø

Pack Terminal Voltage

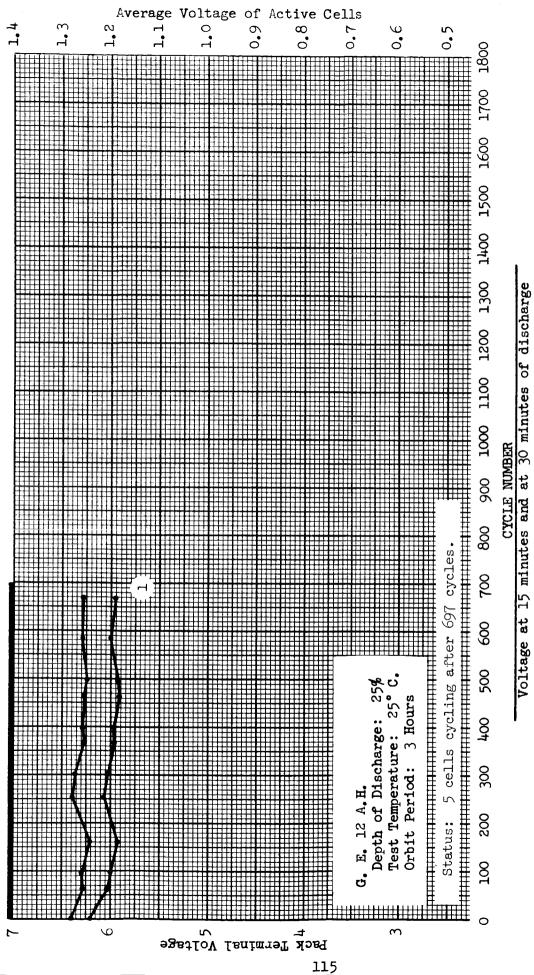
Average Voltage of Active Cells

FIGURE 67

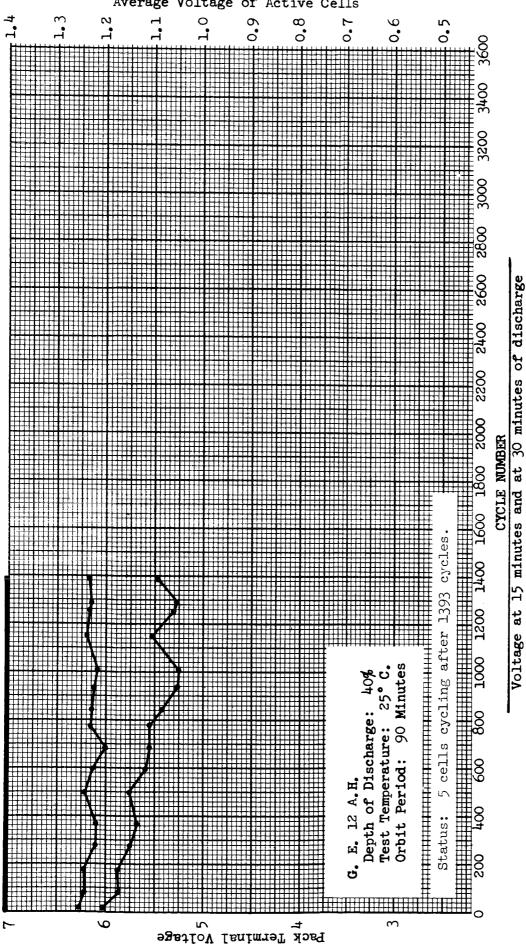








Capacity check followed cycle 693.



116

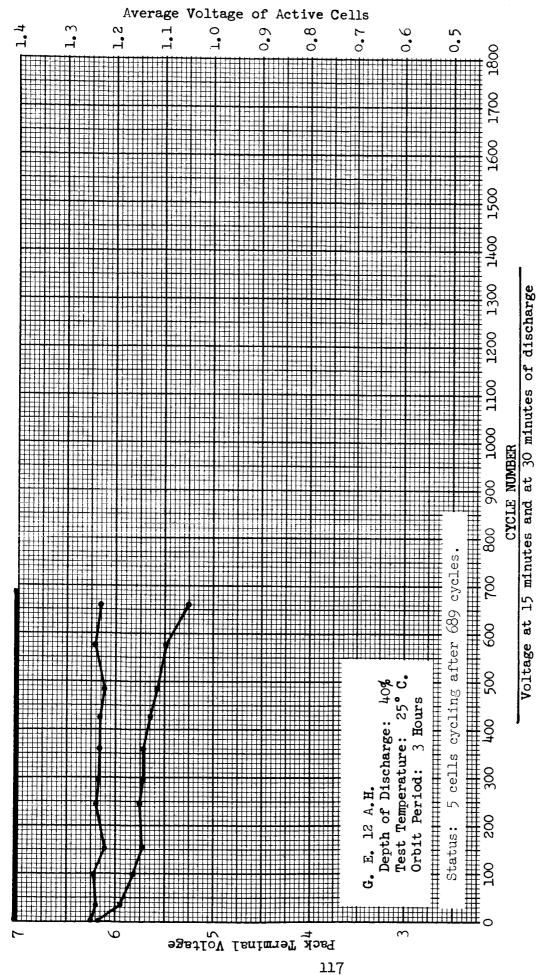


FIGURE 72

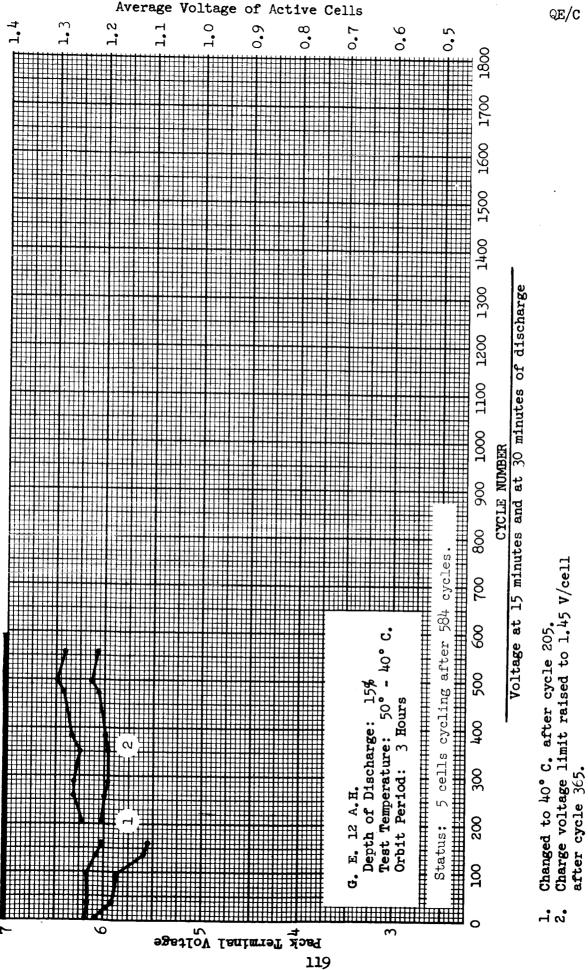
Charge voltage limit raised to 1,45 V/cell

after cycle  $ar{4} eta b$ 

Changed to  $40^{\circ}$  C, after cycle 334,

۲. %







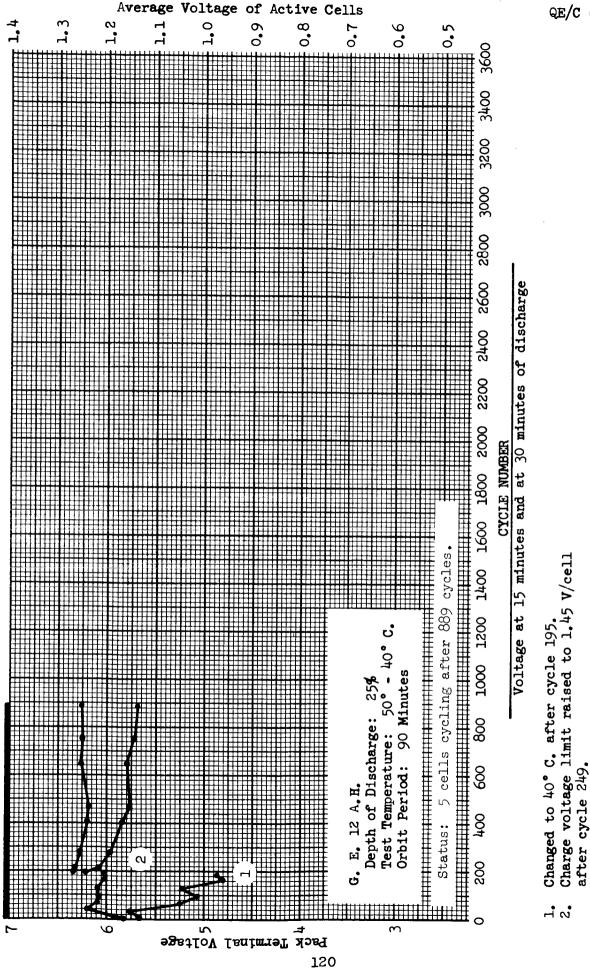
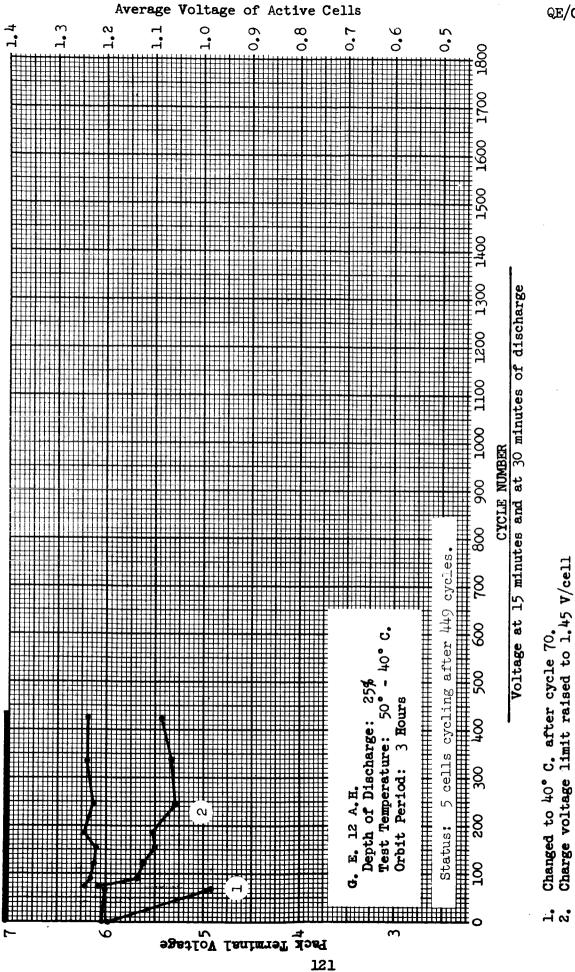


FIGURE 74



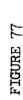


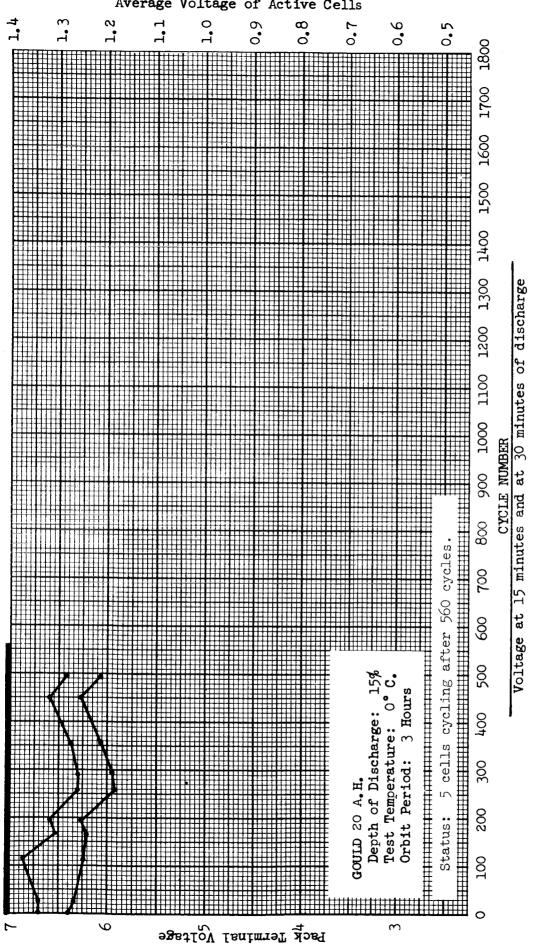
after cycle 230,

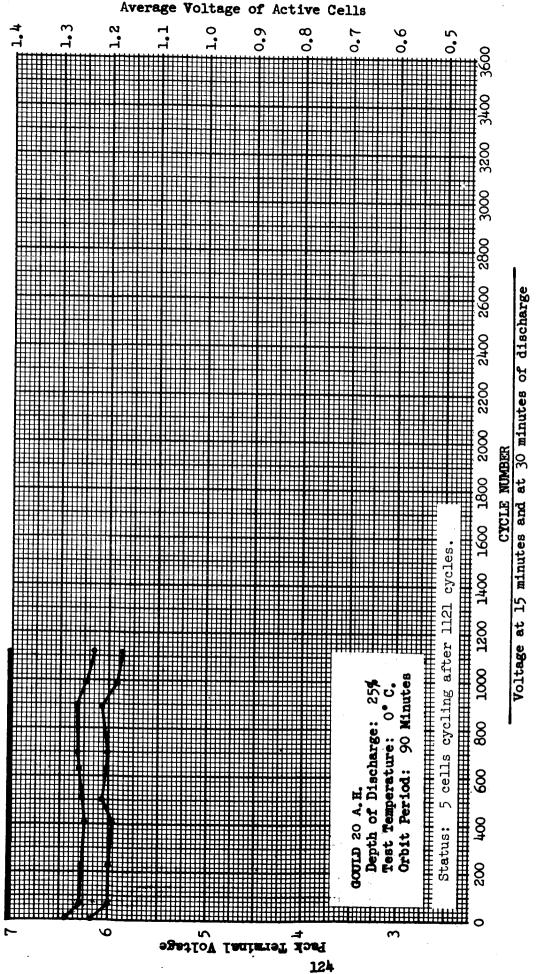
122

Average Voltage of Active Cells

FIGURE 76







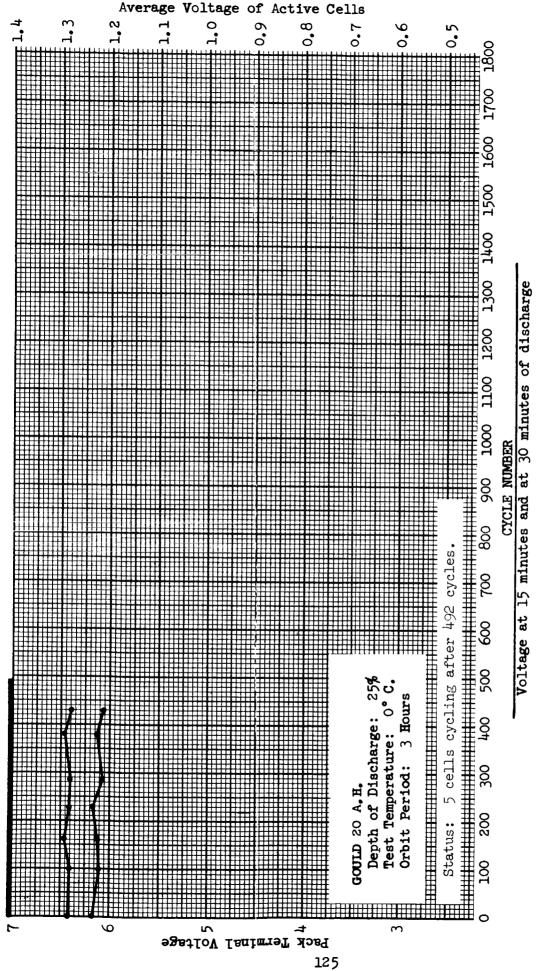
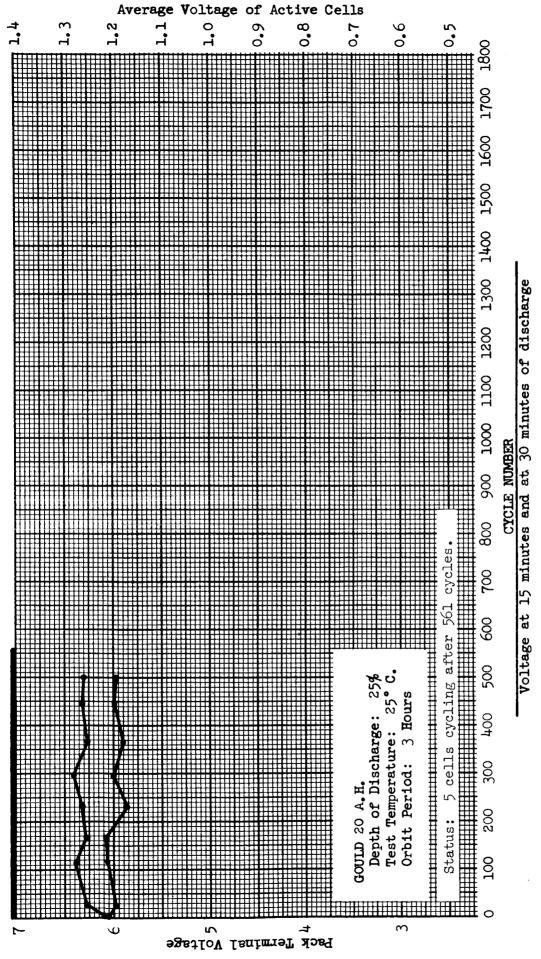


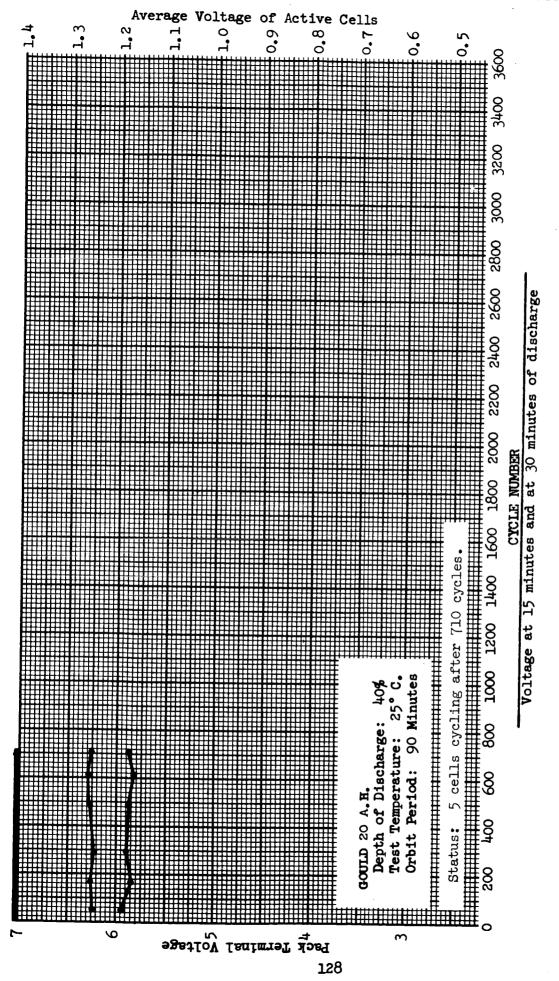
FIGURE 80

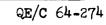


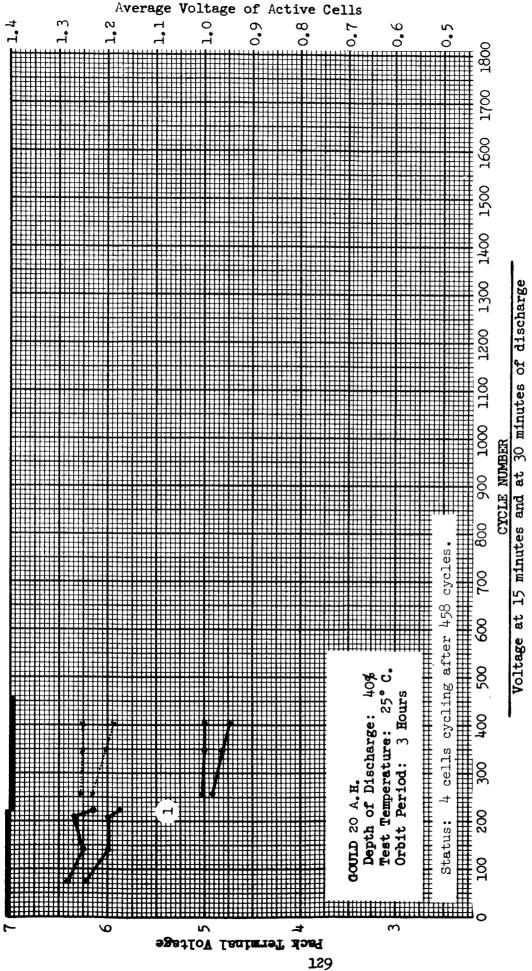


127

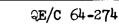








1. Cell number 73 falled on cycle 222.



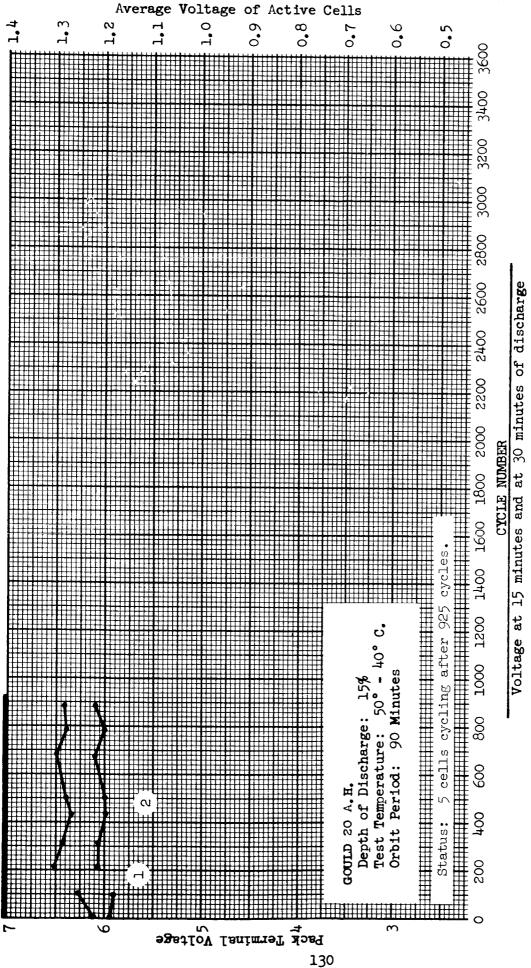


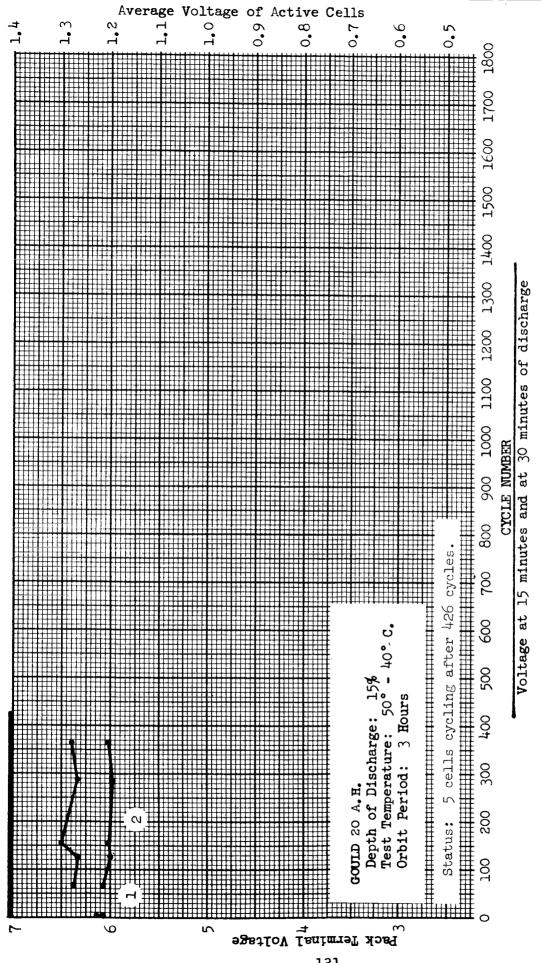
FIGURE 84

Charge voltage limit raised to 1,45 V/cell after cycle 485.

Changed to 40° C. after cycle 183,

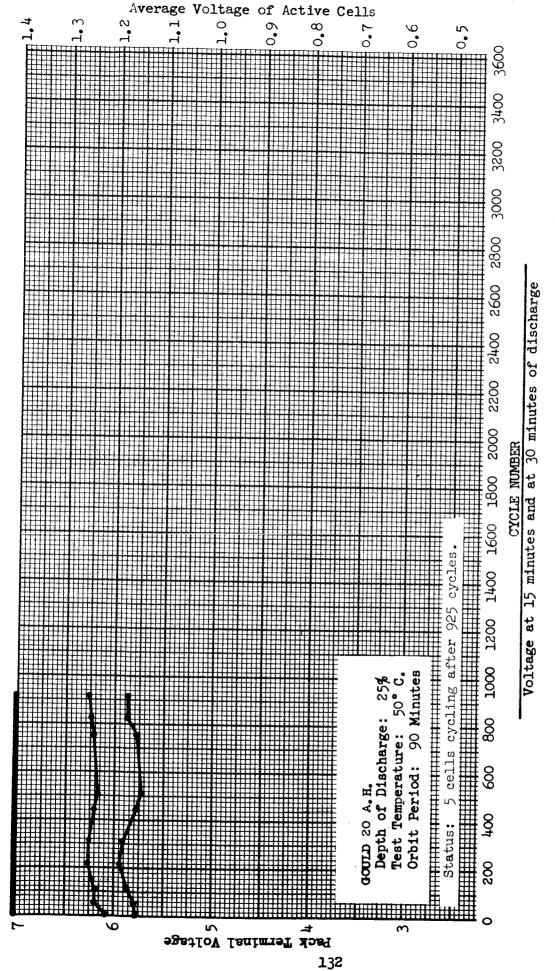
4.5



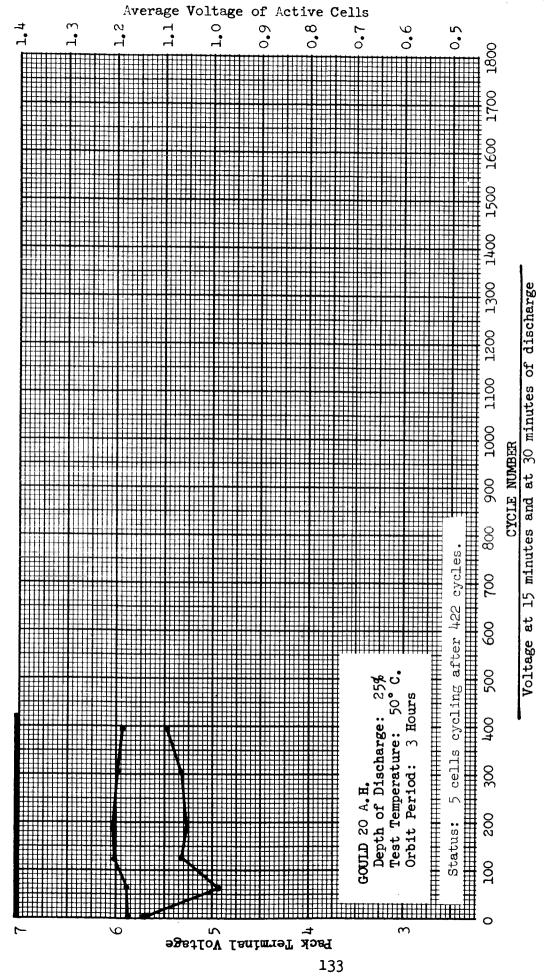


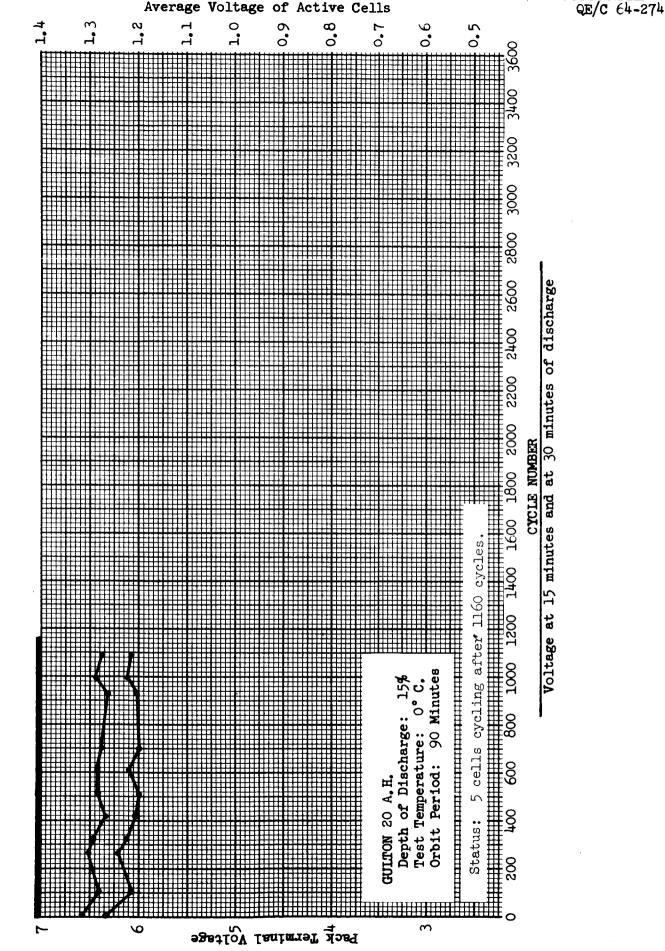
Charge voltage limit raised to 1,45 V/cell after cycle 206. Changed to 40° C. after cycle 47.

۲. °,

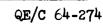








FIGHRE 88



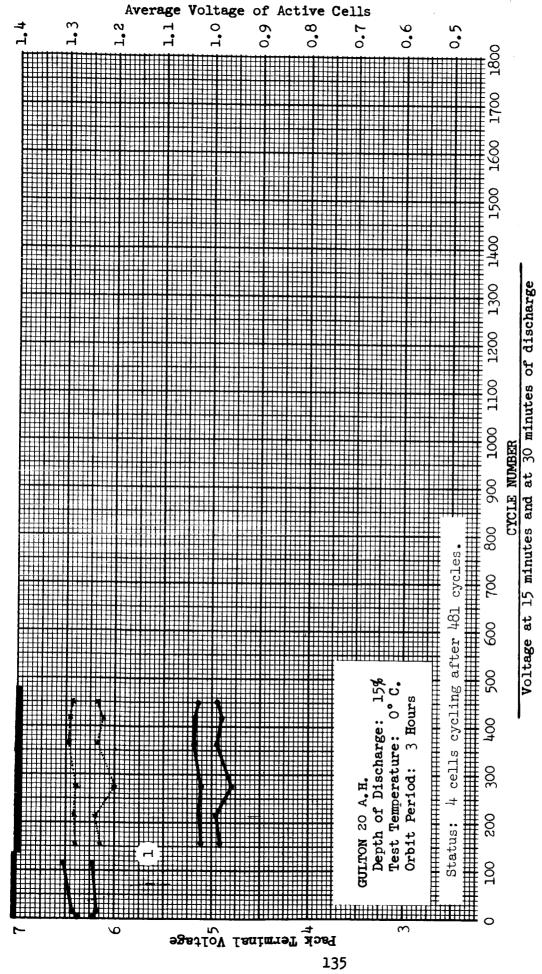


FIGURE 89

Cell number 449 failed on cycle 135.

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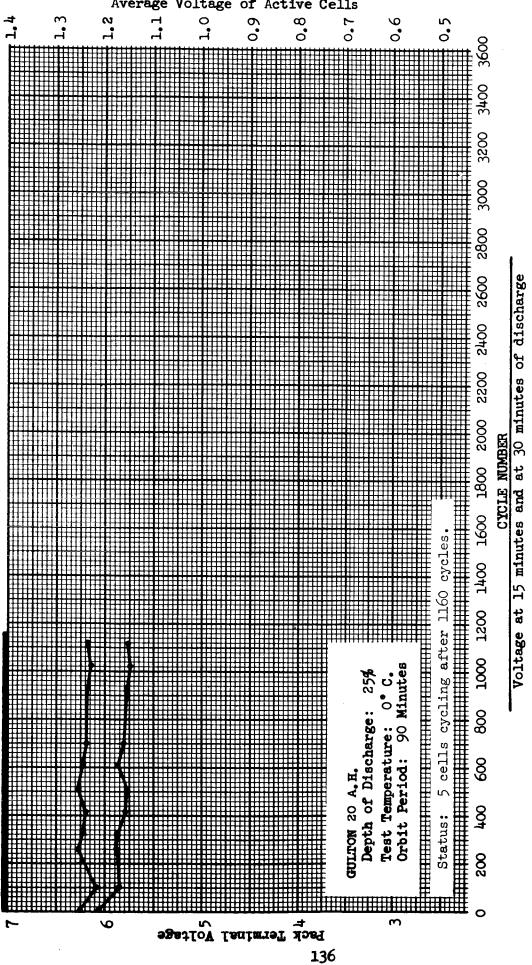
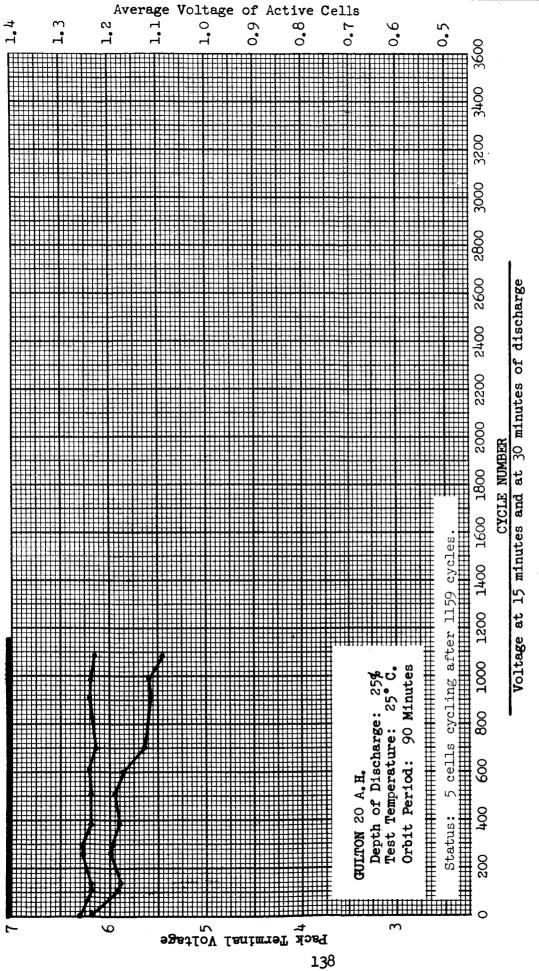
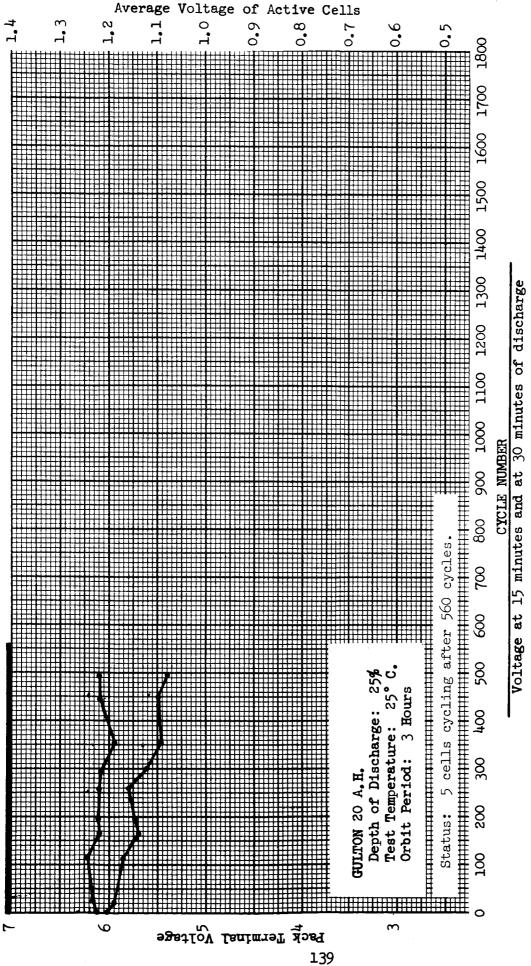


FIGURE 91

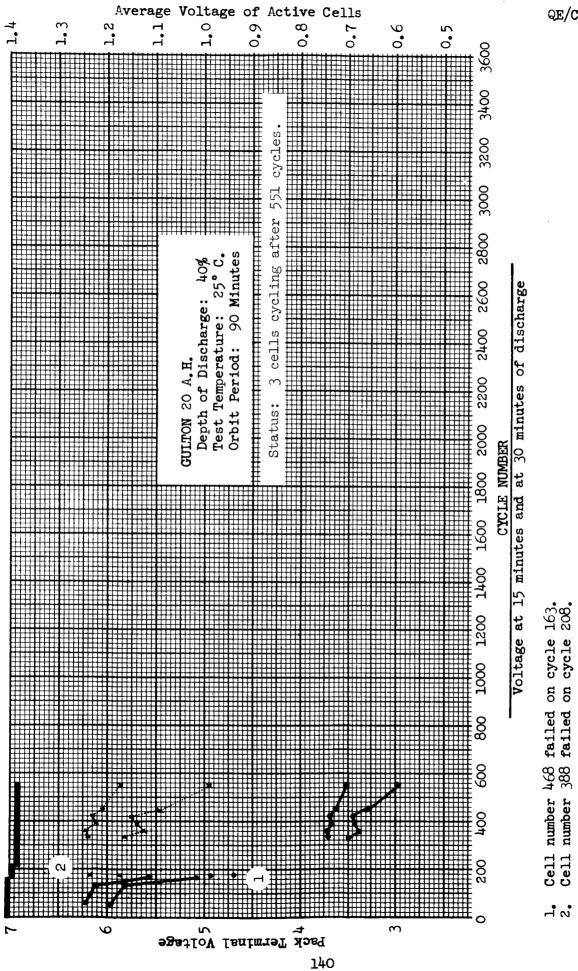














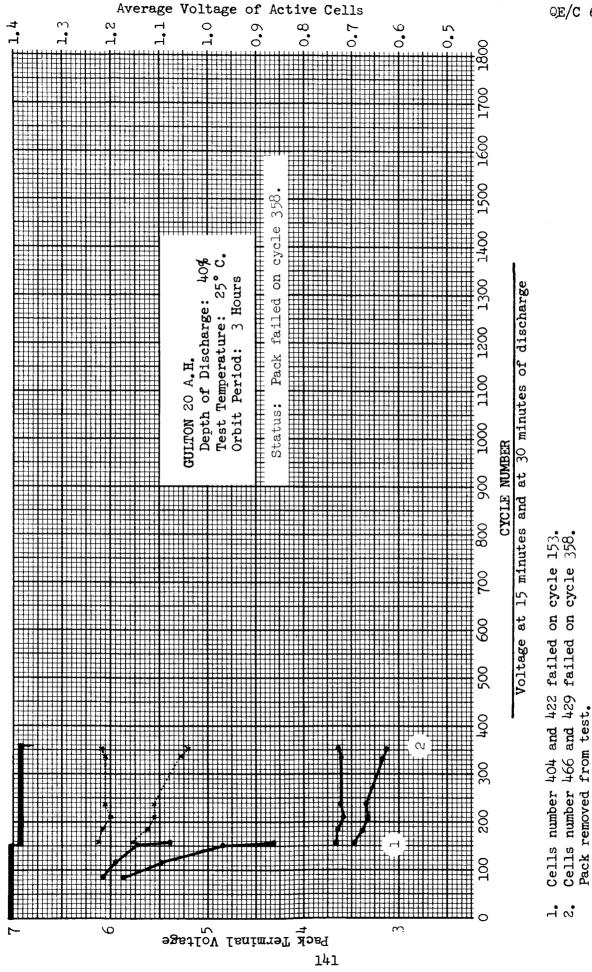
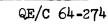


FIGURE 95



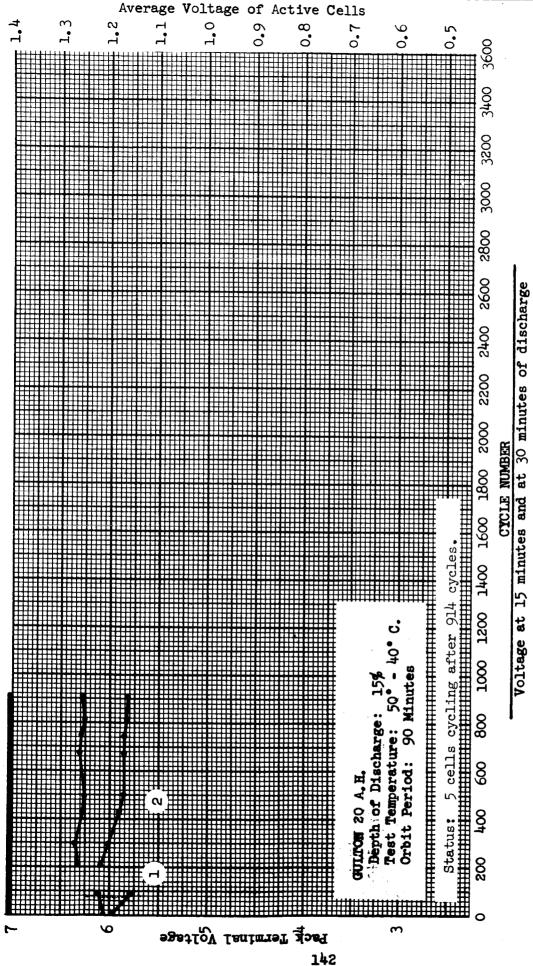


FIGURE 96

Changed to 40° C. after cycle 172. Charge voltage limit raised to 1.45 V/cell

٠<u>.</u> %



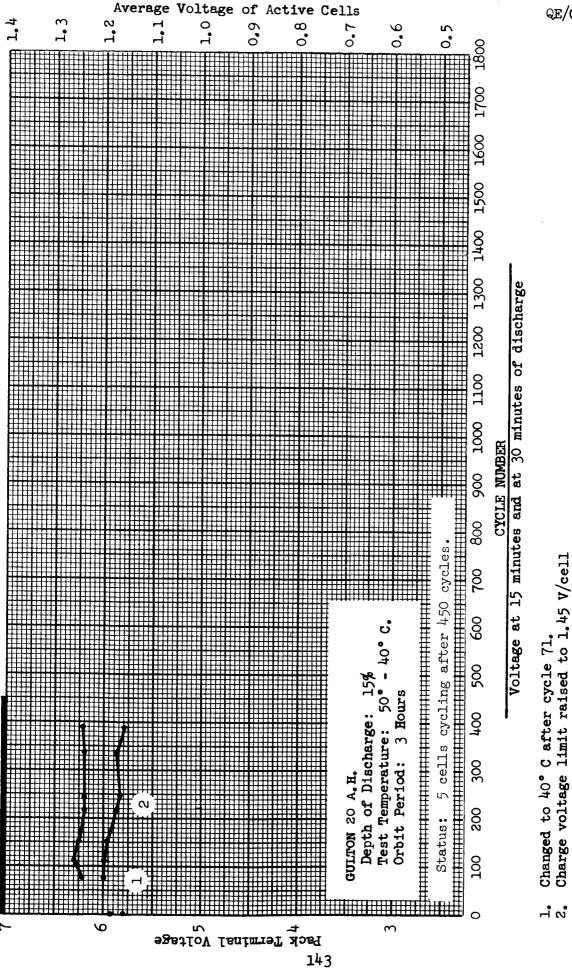


FIGURE 97

۲°,

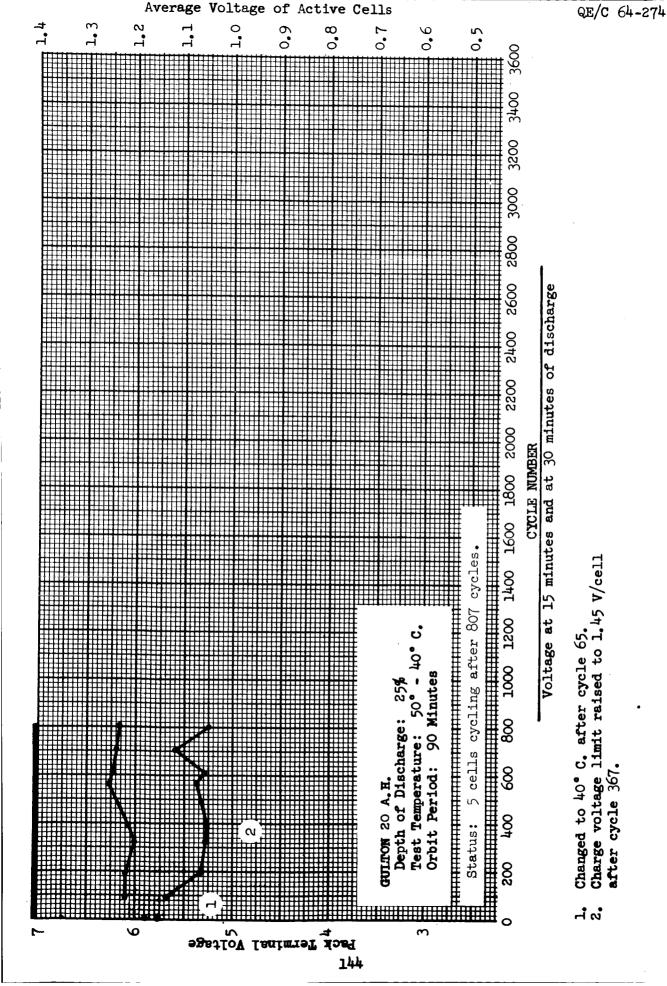


FIGURE 98

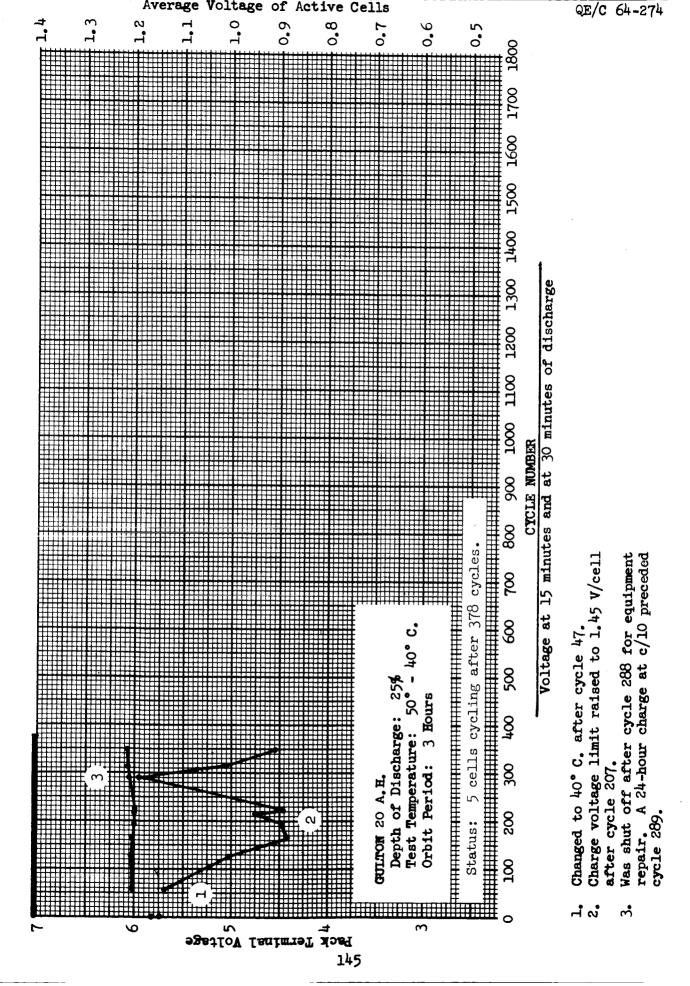


FIGURE 99

## VII. APPENDIX.

- A. Tests to be Added to the Cycle Life Test Program.
  - 1. One pack of five Gulton 6.0 ah cells.
  - 2. One pack of five G.E. 12 ah cells.
- 3. The above two cell types are the same as are described in paragraph II.A. Test parameters are as follows:

Length of Discharge: 1 hour Length of Charge: 23 hours Depth of Discharge: 50 percent Percent of Recharge: 150 percent Ambient Temperature: 25° C

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